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***Quantum Efficiency Characterization of ANTARES
Photomultiplier Tubes for Sustainable Reuse in SWGO***

Abstract

The Southern Wide-field Gamma-ray Observatory (SWGGO) will use water Cherenkov detectors to measure secondary particles produced in gamma-ray-induced air showers. Reusing Hamamatsu R7081-20 photomultiplier tubes recovered from the decommissioned ANTARES neutrino telescope could reduce the cost and material requirements of its photosensor system. Their present wavelength-dependent quantum-efficiency response must therefore be evaluated after long-term deep-sea operation, recovery, extraction, cleaning, and storage, while spatial response measurements can provide additional information for a selected subset.

In this thesis, a laboratory system was designed, constructed, and automated to measure the quantum efficiency of extracted ANTARES photomultiplier tubes. The setup combines a xenon lamp, monochromator, calibrated silicon photodiode, picoammeter, light-tight enclosure, and motorized rotation stage. Complete wavelength-dependent QE spectra were measured for 124 extracted PMTs and the independently measured comparison PMT TM0007. Angular spectral scans were additionally performed on a selected PMT subset to characterize the response across the hemispherical photocathode.

Dedicated systematic studies established the required lamp warm-up period, dark-current treatment, usable photocurrent range, and the effect of the monochromator grating and filter transition near 400 nm. Photodiode normalization removed most of the large optical-throughput discontinuity at this transition from the reconstructed QE.

Across the 124 extracted PMTs, the median peak QE is 25.52 % near 370 nm, with individual peak values ranging from 19.33 % to 29.01 %. TM0007 reaches a peak QE of approximately 24.60 %. Between 400 nm and 500 nm, the extracted-population median is approximately 1.95 percentage points above TM0007; this difference is consistent with the tube-to-tube variation observed in the extracted population.

An automated quality-control pipeline combining robust population statistics, spectral-shape features, PCA reconstruction error, and Isolation Forest ranking was used to select spectra for manual review. Of the 124 extracted-PMT measurements, 114 were retained for population-level QE interpretation, while 10 were assigned to targeted diagnosis or remeasurement. All 114 retained PMTs have reconstructed peak QE values above the historical ANTARES requirement of approximately 20 %.

At population level, the spectral measurements provide no evidence for a uniform reduction of wavelength-dependent photocathode sensitivity. Within the selected spatial-scan subset, the measured PMTs show a broad central response region, with the strongest variations concentrated near the photocathode boundary. These measurements characterize the selected subset and do not establish the frequency of such spatial behaviour across the complete recovered population. No statistically supported dependence of peak QE on the original ANTARES line or storey position was found.

The retained spectral population therefore forms the main QE-based candidate pool for complementary electrical, timing, spatial, and detector-level reuse qualification within the SWGGO programme.

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Cosmic Rays and Gamma Rays	2
1.3	Need for Reliable Photosensors in SWGO	3
1.4	Research Objectives and Scope	3
2	Gamma-Ray Astronomy and Detection Principles	5
2.1	Understanding Gamma-rays	5
2.2	Gamma-Ray Sources and Detection Mechanisms	7
2.2.1	Gamma-Ray Sources	7
2.2.2	Production Mechanisms	8
2.2.3	Detection Mechanisms	10
2.3	Cosmic-Ray Background and Extensive Air Showers	14
2.3.1	Hadronic and Electromagnetic Shower Components	14
2.3.2	Electromagnetic Shower Development	15
2.3.3	Lateral Structure of the Shower	16
2.4	Cherenkov Radiation	17
2.4.1	Cherenkov Light Detection in Water Cherenkov Tanks	19
2.5	Air-Shower Detection and Event Identification	20
2.5.1	Gamma-Hadron Separation in WCD Arrays	20
2.5.2	Shower Reconstruction in WCD Arrays	21
2.6	Role of Photon Detection in WCD Performance	22
3	Legacy & Future: ANTARES & SWGO	23
3.1	ANTARES Experiment	23
3.1.1	Detector and Optical Module Overview	24
3.1.2	Storey and Optical Module Architecture	25
3.2	ANTARES Photomultiplier Extraction	25
3.3	SWGO: Southern Wide-field Gamma-ray Observatory	27
3.3.1	Array Layout and Site Characteristics	28
3.3.2	Double-Layer Water Cherenkov Detector Design	29

4	Photomultiplier Tubes and Quantum Efficiency Fundamentals	33
4.1	Photomultiplier Tubes in the ANTARES Optical Module	33
4.2	Operating Principle of a Photomultiplier Tube	34
4.3	Quantum Efficiency as a Measure of Photon Sensitivity	36
4.3.1	Wavelength Dependence and Detection Efficiency	37
4.4	Operational Performance Parameters and Relevance for SWGO Reuse	38
5	Experimental Setup and Measurement Methodology	41
5.1	Experimental Setup: Design, Construction, and Validation	41
5.1.1	Construction	42
5.1.2	Light-Tight Validation	47
5.2	Instrument Control and Data Acquisition	48
5.2.1	Automation Rationale and Measurement Workflow	49
5.3	Calibration, Stability, and Systematic Effects	50
5.3.1	Integrated Measurement-Control and Wavelength Readback	50
5.3.2	Monochromator Communication, Optical Configuration, and Transition Systematics	50
5.3.3	Instrumental Systematic near the UV–Visible Transition	53
5.3.4	Lamp Warm-Up and Optical-Flux Stability	56
5.3.5	Dark-Current Integration and Drift Treatment	58
5.3.6	Angular-Scan Procedure and Rotation-Stage Calibration	61
5.4	Photodiode Calibration	62
5.5	Photomultiplier Quantum-Efficiency	63
6	Data Processing and Measurement-Quality Assessment	69
6.1	Overview of the Measured Dataset	69
6.2	Why Quality Control is Required Before Aging Analysis	69
6.2.1	Measurement Artifacts that Mimic Aging	69
6.2.2	Slit-Width Transition Effects	70
6.2.3	Dark-Current Drift and Low-Current Sensitivity	73
6.2.4	Iris-Opening and Photocurrent-Flux Tests	74
6.3	Traditional Quality-Control	76
6.4	Unsupervised Machine Learning for Quality Control	76
6.4.1	Population Median and MAD Reference	76
6.4.2	Shape-Based Anomaly Features	77
6.4.3	PCA Reconstruction Error	78
6.4.4	Isolation Forest	78
6.5	Quality-Control Scoring and Results	79
6.5.1	Automated Anomaly-Screen Output	80
6.5.2	Manual Review and Measurement Disposition	82

7	Quantum Efficiency and Aging Analysis of Extracted ANTARES PMTs	87
7.1	Population-Level Quantum-Efficiency Results	87
7.2	Comparison with Reference PMT TM0007	89
7.3	Post-QC Aging Interpretation and QE-Based Reuse Indicators	92
7.4	Outlier and Case-Study PMTs	95
7.5	Line and Storey Dependence	100
7.5.1	Line 4 vs Line 8 Comparison	100
7.5.2	Storey-Position Correlation	102
8	Angular Quantum-Efficiency Response of Extracted ANTARES PMTs	105
8.1	Motivation for Angular QE Measurements	105
8.2	Rotation Geometry and Photocathode Coverage	106
8.3	Angular Dependence of the QE Spectrum	108
8.4	Spatial QE Response and Dynode-Orientation Dependence	110
8.4.1	Dynode-Orientation Configurations	110
8.4.2	Photomultiplier Spatial Response	111
8.4.3	Angular Zero-Offset Correction	115
8.4.4	Understanding Dynode-Orientation Dependence	116
8.5	Interpretation of the Spatial QE Response	119
9	Discussion, Implications and Outlook	123
9.1	Reliability of the QE Assessment	123
9.2	Implications for the Recovered PMT Population	124
9.3	Implications of the Spatial-Response Measurements	124
9.4	Next Steps for Reuse Qualification	125
9.5	Overall Assessment	125
	Acronyms	126
A	Supplementary Material	129
A.1	Dark-Current Stabilization Examples	129
A.2	Angular QE Measurement Procedure	130
A.3	Autosaving, Emergency Saving, and Reproducibility	131
A.4	Ranked PMT Quantum-Efficiency Summary	131
A.5	REVIEW Quality-Control Spectra	133
A.6	Mild Spatial Degradation	136
A.7	Control Scripts and Quality Control Pipeline	137
	Bibliography	139

Chapter 1

Introduction

1.1 Motivation

“Nothing in life is to be feared, it is only to be understood.”
— Marie Curie

Science is driven by the desire to understand what lies beyond immediate experience. In astrophysics, this curiosity leads to the study of some of the most extreme environments in the Universe, including supernova remnants, pulsar wind nebulae, and active galactic nuclei. Observations of such systems provide insight into non-thermal processes, particle acceleration, and the origin of cosmic rays. At the same time, progress in this field depends closely on the development of suitable instrumentation, since advances in detector technology often determine which physical questions can be addressed at all.

Marie Curie’s remark reflects an idea that is central to this work: scientific understanding does not begin with certainty, but with the willingness to engage with what is not yet clear. The initial encounter with this topic was marked by the challenge of building understanding from the most fundamental concepts upward. Over time, however, the process of learning, questioning, and gradually resolving that complexity became a major motivation for this thesis. The work is therefore driven not only by the scientific relevance of high-energy astrophysics, but also by the conviction that even demanding detector and measurement problems can be approached systematically and understood in a rigorous way.

The Southern Wide-field Gamma-ray Observatory (SWGGO) is expected to become an important new facility in ground-based gamma-ray astronomy. In order to achieve its scientific goals, it requires a detector concept that combines large area, good sensitivity, long-term stability, and practical cost effectiveness. As in many large astroparticle-physics experiments, the scientific reach of the observatory depends not only on ambitious physics objectives, but also on the reliability and performance of the underlying instrumentation [3].

Against this background, it is natural to ask whether the observatory can be realized in a way that is both technically robust and resource-conscious. One possible approach is the reuse of photomultiplier tubes recovered from the decommissioned ANTARES neutrino telescope. Such reuse could reduce both cost and material demand, but it first requires a quantitative assessment of whether the photocathodes of these previously deployed sensors have retained their wavelength-dependent and spatial sensitivity after extraction, cleaning, storage, and laboratory handling.

This thesis addresses that question through the development of a dedicated and automated quantum-efficiency measurement setup. The work comprises spectral measurements of 124 extracted ANTARES PMTs, a population-level characterization of their QE response, and spatial

measurements across the photocathode surface. In this way, the thesis combines the broader motivation of resource-conscious detector development with a clearly defined experimental task: determining how well the recovered PMTs have preserved their photocathode sensitivity.

1.2 Cosmic Rays and Gamma Rays

SWGO will detect not only gamma-ray-induced air showers, but also the much more abundant showers initiated by cosmic rays. Cosmic rays are energetic charged particles that continuously arrive at Earth from space. They consist predominantly of protons and heavier nuclei, and their energies extend from the MeV scale to beyond 10^{20} eV. Their all-particle energy spectrum follows an approximate power law and contains characteristic structures such as the knee, second knee, and ankle, which provide important clues about the origin and propagation of high-energy particles [24].

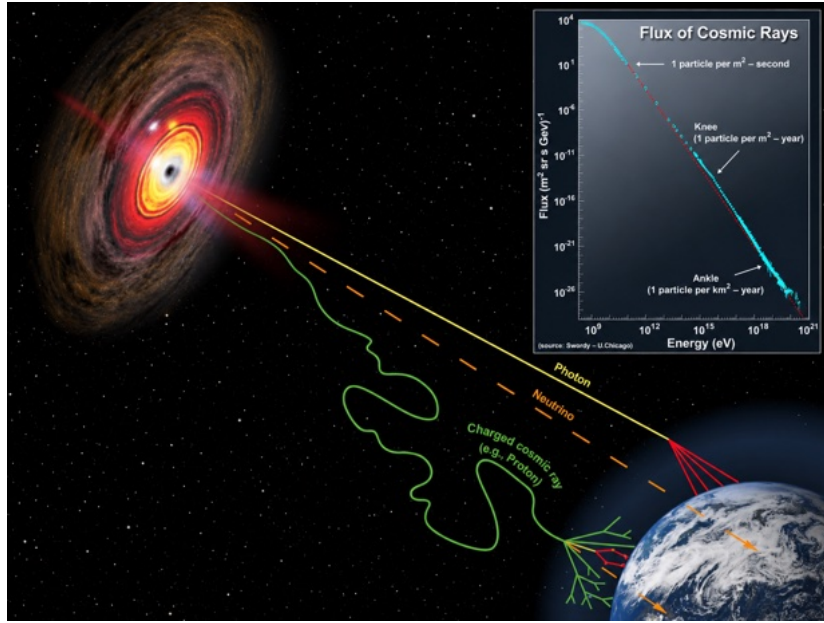


Figure 1.1: Schematic comparison of different cosmic messengers from an astrophysical source. Photons and neutrinos travel approximately along the source direction, while charged cosmic rays are deflected by magnetic fields and therefore do not generally point back to their origin. Adapted from [17].

At relatively low energies, cosmic rays can be measured directly above the atmosphere using balloon- or satellite-borne instruments. At higher energies, the rapidly decreasing flux makes direct measurements with balloon- or satellite-borne instruments impractical. The primary particle must therefore be studied indirectly through the extensive air shower it produces in the atmosphere[24].

A central limitation of cosmic-ray astronomy is that the primary cosmic rays observed at Earth are predominantly charged. Their trajectories are deflected by Galactic and interstellar magnetic fields, so their arrival directions at Earth usually do not point back to their sources. Gamma rays, by contrast, are electrically neutral and can preserve directional information during propagation. They therefore provide an im-

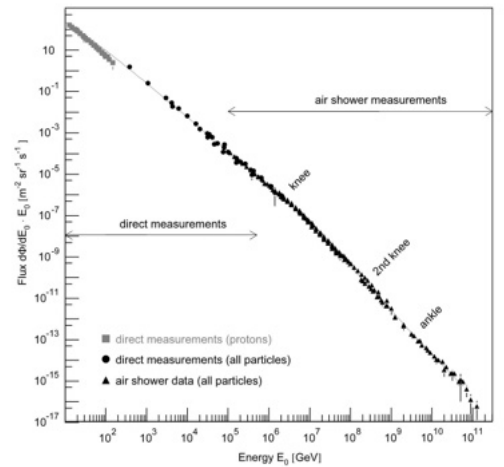


Figure 1.2: All-particle cosmic-ray energy spectrum showing characteristic features such as the knee, second knee, and ankle. Adapted from [24].

portant complementary messenger for identifying and studying high-energy astrophysical sources. At very high energies, gamma rays can also be detected indirectly through the atmospheric air showers they initiate. In ground-based gamma-ray astronomy, hadronic cosmic rays form the dominant background because they produce air showers far more frequently than astrophysical gamma rays. The task of an observatory such as SWGO is therefore not only to detect air showers, but to distinguish gamma-ray-induced events from this hadronic background. The detailed physics of electromagnetic and hadronic shower development, including their different particle content and detector signatures, is discussed in Chapter 2.

1.3 Need for Reliable Photosensors in SWGO

The performance of SWGO depends on the stable and well-characterized response of the photosensors in its water Cherenkov detector units. These sensors convert Cherenkov light produced by secondary shower particles into measurable electrical signals and therefore directly influence the detector response.

The decommissioning of ANTARES provides a potential source of large-area Hamamatsu R7081-20 PMTs. However, their suitability for reuse must be verified after long-term deep-sea operation, recovery, extraction, cleaning, storage, and laboratory handling.

This thesis evaluates the wavelength-dependent and spatial quantum efficiency of the recovered PMTs to determine whether their photocathodes have retained sufficient sensitivity and to support the selection of tubes for further reuse qualification.

1.4 Research Objectives and Scope

The primary objective of this thesis is to provide a systematic post-recovery characterization of the wavelength-dependent and spatial quantum-efficiency response of photomultiplier tubes extracted from the ANTARES neutrino telescope. The study investigates whether their photocathodes have retained their sensitivity after long-term operation, recovery, cleaning, storage, and laboratory handling.

To achieve this objective, a dedicated laboratory setup was designed, constructed, and automated for reproducible QE measurements. The experimental and analytical programme comprises the following tasks:

- development and automation of a measurement system for wavelength-dependent PMT photocurrent measurements;
- calibration of the incident optical flux using a calibrated silicon photodiode;
- characterization of instrumental systematics, including lamp stability, dark-current drift, low-current sensitivity, and monochromator transition effects;
- measurement of the spectral QE response of 124 extracted ANTARES PMTs;
- derivation of spectral quantities including peak QE, mean QE in the 300 nm to 500 nm range, Cherenkov-weighted QE, and spectral-shape indicators;
- comparison of the extracted PMT population with the TM0007 reference PMT and the original ANTARES peak-QE requirement of 20 %;
- identification of measurement artefacts that could otherwise be misinterpreted as changes in photocathode performance;

- population-level characterization of the measured QE distributions and spectral shapes;
- spatial characterization of the photocathode response through angular QE measurements at different illumination positions and dynode orientations;
- automated classification of the measured spectra into **GOLD**, **SILVER**, **BRONZE**, or **REVIEW** quality-control tiers, followed by manual measurement disposition and separate identification of low-QE spectra.

Together, these measurements establish how the spectral response varies across the recovered PMT population and how the QE changes across the photocathode surface. The resulting analysis distinguishes consistent photocathode behaviour from instrumental distortions and identifies PMTs whose QE response differs substantially from the reference behaviour or from the measured population.

The wider reuse programme includes complementary electrical, timing, and detector-integration studies; these are summarized in the Outlook but are not part of the experimental programme presented here.

Beyond the characterization of the individual PMTs, this work demonstrates a measurement strategy for evaluating recovered photosensors using reproducible calibration, systematic-error studies, population comparison, and spatial response measurements. The resulting procedure provides a reproducible method for measuring and comparing the spectral and spatial QE of recovered photosensors.

Chapter 2

Gamma-Ray Astronomy and Detection Principles

2.1 Understanding Gamma-rays

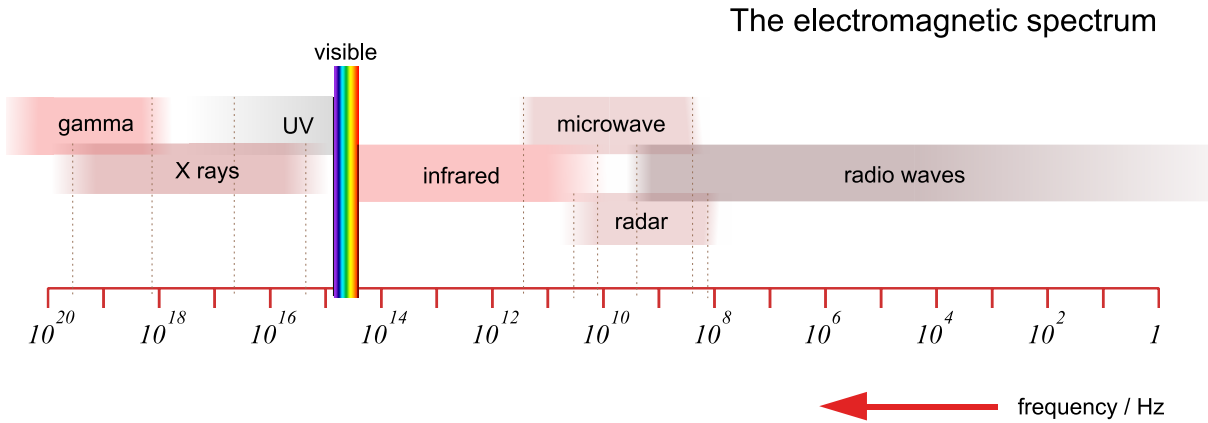


Figure 2.1: Electromagnetic spectrum. Adapted from [10].

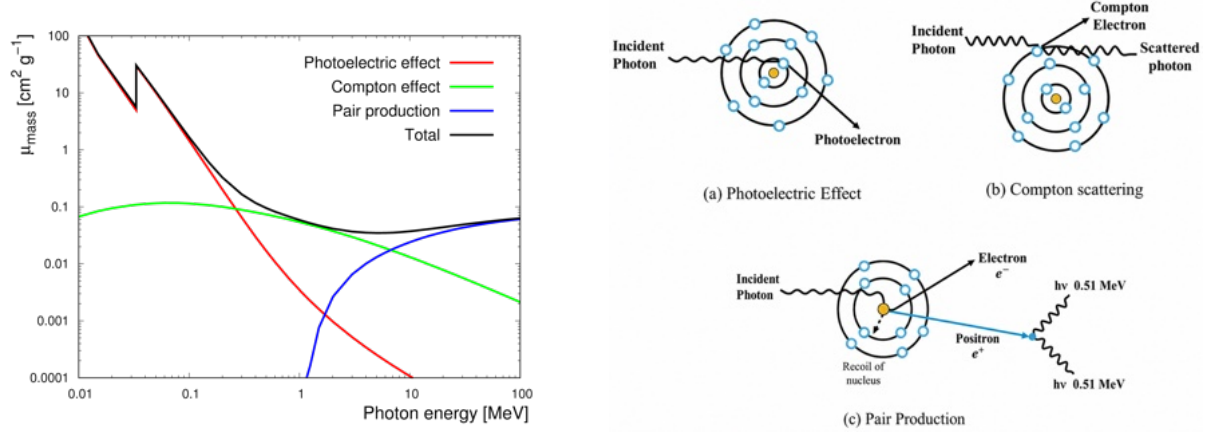
Gamma rays occupy the highest-energy region of the electromagnetic spectrum, extending from the MeV range to GeV, TeV, and, in the most extreme astrophysical observations, even PeV energies. Their energy is related to frequency through Planck's relation, $E = h\nu$, and their short wavelengths distinguish them from lower-energy radiation such as X-rays, ultraviolet, optical, infrared, and radio emission. In high-energy astrophysics, gamma rays are especially important because they trace energetic and often non-thermal environments in the Universe [19].

Because gamma rays are electrically neutral, their arrival directions can preserve information about their production sites, making them a direct astronomical messenger at high energies.

Astrophysical gamma rays are produced mainly by relativistic particles. Electrons and positrons can generate gamma rays through inverse Compton scattering and bremsstrahlung, while protons and heavier nuclei can produce gamma rays through hadronic interactions followed by neutral-pion decay, $\pi^0 \rightarrow \gamma\gamma$. Since leptonic and hadronic scenarios can sometimes produce similar gamma-ray signatures, the interpretation of gamma-ray sources usually requires spectral, morphological, and multi-wavelength information [19].

The interaction probability of gamma rays with matter depends on both the photon energy and the absorber material. For lead, the photoelectric effect dominates at low photon energies, Compton

scattering is most important over an intermediate energy range, and electron–positron pair production becomes dominant at sufficiently high energies. Pair production becomes energetically possible above the threshold energy of 1.022 MeV and occurs predominantly in the Coulomb field of an atomic nucleus, which absorbs the recoil momentum. These processes are summarized in Fig. 2.2 [19].



(a) Mass attenuation coefficients in lead for the photoelectric effect, Compton scattering, and pair production as a function of photon energy.

(b) Schematic representation of the photoelectric effect, Compton scattering, and pair production. In pair production, the photon converts into an electron–positron pair in the nuclear Coulomb field, and the nucleus absorbs the recoil momentum.

Figure 2.2: Principal gamma-ray interaction processes in matter. The left panel shows their energy-dependent contributions to the mass attenuation coefficient in lead. The right panel illustrates the corresponding interaction mechanisms. The positron produced during pair production subsequently loses energy and annihilates with an electron, usually producing two photons of approximately 0.511 MeV. Adapted from [30, 8].

These interactions determine how gamma rays transfer energy to matter. The Earth’s atmosphere absorbs gamma rays before they reach the ground, so direct measurements are performed with space-based instruments. At higher energies, the low photon flux and limited effective area of satellite instruments make direct detection inefficient. Ground-based observatories instead detect the extensive air showers initiated when primary gamma rays interact in the atmosphere. The energy and direction of the primary gamma ray are reconstructed from the secondary shower particles or from the radiation they produce [19].

Space-based and ground-based instruments therefore cover different energy ranges. Space-based telescopes operate mainly in the MeV–GeV range, whereas ground-based observatories extend gamma-ray measurements into the TeV and PeV regimes through indirect air-shower detection.

2.2 Gamma-Ray Sources and Detection Mechanisms

2.2.1 Gamma-Ray Sources

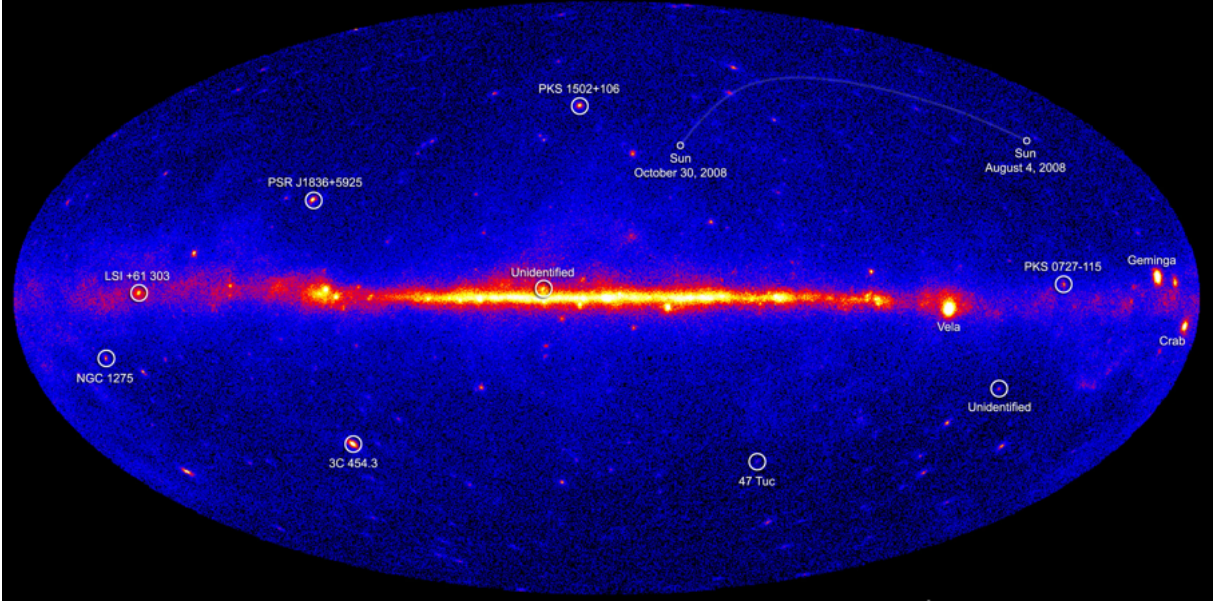


Figure 2.3: All-sky gamma-ray map from the Fermi Gamma-ray Space Telescope. Adapted from [45].

Gamma-ray sources are astrophysical objects or regions in which particles are accelerated to relativistic energies and produce high-energy photons through non-thermal processes. The gamma-ray sky contains both diffuse Galactic emission and individual compact or extended sources, as shown in Fig. 2.3. Diffuse emission is strongest along the Galactic plane, where cosmic rays interact with interstellar gas, dust, and radiation fields, while individual sources trace localized regions of particle acceleration [19].

For very-high-energy and ultra-high-energy gamma-ray astronomy, the most relevant source classes are those associated with particle acceleration to the TeV and PeV regimes. Galactic examples include pulsar wind nebulae, supernova remnants, TeV halos, massive stellar clusters, binary systems, and the Galactic Centre region. These sources are central to the broader question of how particles are accelerated to extreme energies and whether Galactic objects can act as PeVatrons [19, 3].

The Crab Nebula is a key reference source in gamma-ray astronomy. Powered by the Crab pulsar, it emits non-thermal radiation across a wide wavelength range, from radio emission to very-high-energy gamma rays. Its brightness and long observational history make it an important benchmark for particle-acceleration studies, multiwavelength modelling, and detector performance [9].

Extragalactic gamma-ray sources, particularly active galactic nuclei and gamma-ray bursts, contribute a strongly variable component to the high-energy sky. In blazars, the relativistic jet is directed close to the observer's line of sight, so Doppler boosting enhances the ob-

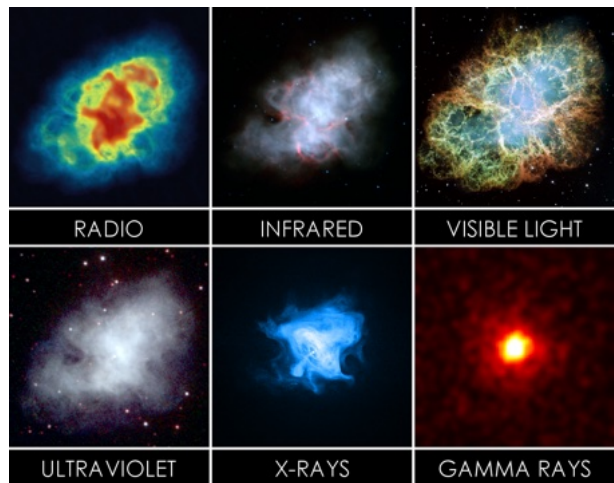


Figure 2.4: Multiwavelength view of the Crab Nebula. [36].

served emission and compresses the apparent variability timescales. Gamma-ray bursts are even more transient, producing intense emission over timescales from milliseconds to minutes. Because such events are difficult to predict, they are best studied with wide-field observatories that operate with a high duty cycle [19].

The diversity of gamma-ray sources reflects the variety of environments in which relativistic particles are produced. However, the central physical question remains whether the observed gamma rays are produced mainly by accelerated electrons or by accelerated hadrons. This distinction motivates the discussion of gamma-ray production mechanisms in the next section.

2.2.2 Production Mechanisms

High-energy gamma rays are produced when relativistic particles interact with matter, radiation fields, or magnetic fields. In astrophysical sources, these particles are usually non-thermal and can be grouped into two broad populations: leptons, mainly electrons and positrons, and hadrons, mainly protons and heavier nuclei. The corresponding gamma-ray production channels are therefore commonly described as leptonic or hadronic. This distinction is important because leptonic emission traces energetic electron populations, whereas hadronic emission can indicate interactions of accelerated cosmic-ray nuclei with surrounding matter [19].

In **leptonic** scenarios, gamma-ray emission is produced by relativistic electrons or positrons. The most important process at GeV–TeV energies is inverse Compton scattering, where energetic electrons transfer energy to low-energy photon fields such as the cosmic microwave background, infrared radiation, or optical starlight boosting the photons to gamma-ray energies. Non-thermal bremsstrahlung can also contribute when relativistic electrons interact with ambient gas. Since the same electron population can also produce synchrotron radiation at lower photon energies, leptonic models are usually tested using multi-wavelength observations rather than gamma-ray data alone [19].

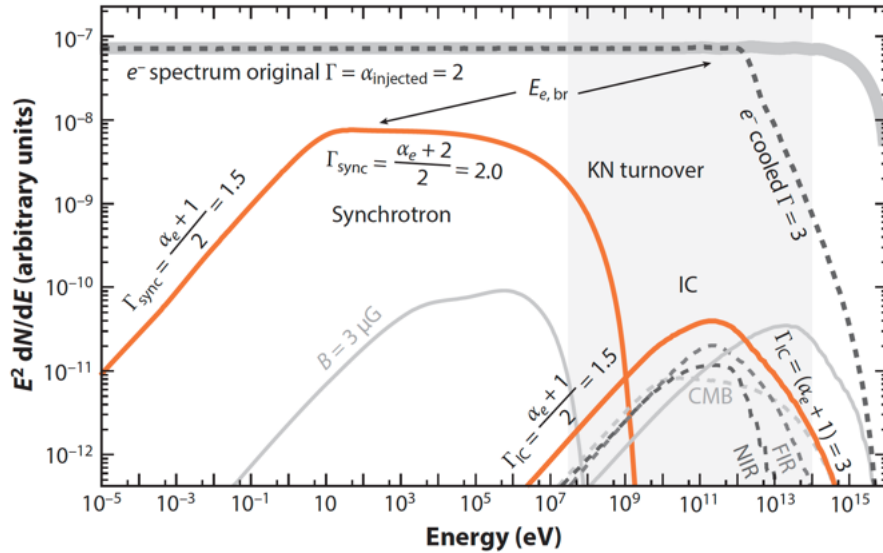


Figure 2.5: Example of a leptonic spectral energy distribution showing synchrotron and inverse Compton components. Synchrotron emission traces the relativistic electron population at lower photon energies, while inverse Compton scattering can extend the emission into the gamma-ray band. Adapted from [19].

This connection is illustrated in Fig. 2.5, where the same relativistic electron population produces synchrotron emission at lower photon energies and inverse-Compton emission in the gamma-ray band.

In **hadronic** scenarios, gamma rays are produced when relativistic protons or heavier nuclei

interact with ambient matter. A representative inelastic proton–proton collision is

$$p + p \rightarrow p + p + \pi^0, \quad (2.1)$$

although several charged and neutral pions may be produced at higher collision energies. The neutral pion is unstable and decays almost immediately into two gamma-ray photons,

$$\pi^0 \rightarrow \gamma + \gamma. \quad (2.2)$$

Because the gamma-ray emission originates from interactions of accelerated hadrons, the detection of this component can provide evidence for cosmic-ray acceleration. The production rate is enhanced in dense environments, such as molecular clouds or shocked interstellar material, where energetic protons encounter a larger density of target nuclei [19].

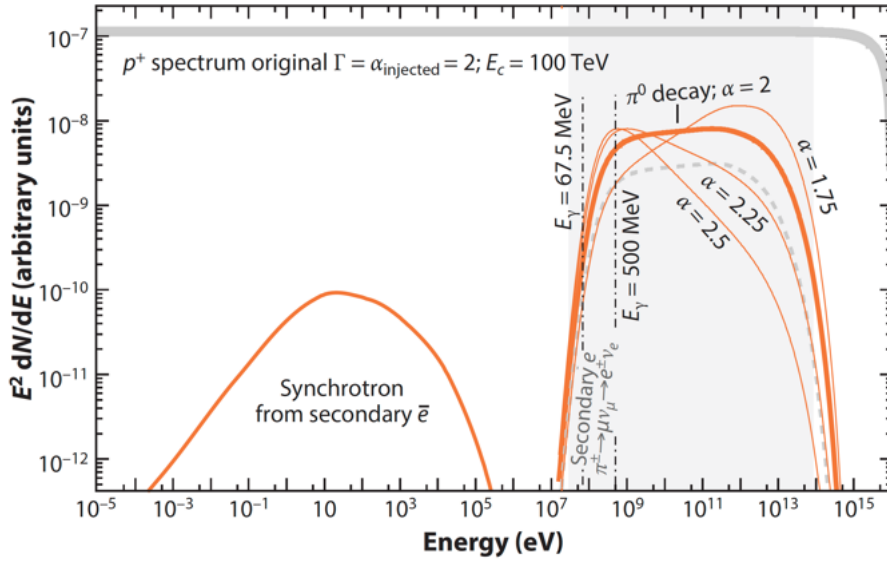


Figure 2.6: Hadronic spectral energy distribution showing the gamma-ray component from neutral-pion decay and the contribution from secondary electrons. Adapted from [19].

Figure 2.6 illustrates how neutral-pion decay can produce a characteristic gamma-ray component in hadronic source models. This makes the hadronic channel central to the interpretation of gamma-ray sources as possible accelerators of protons or heavier nuclei.

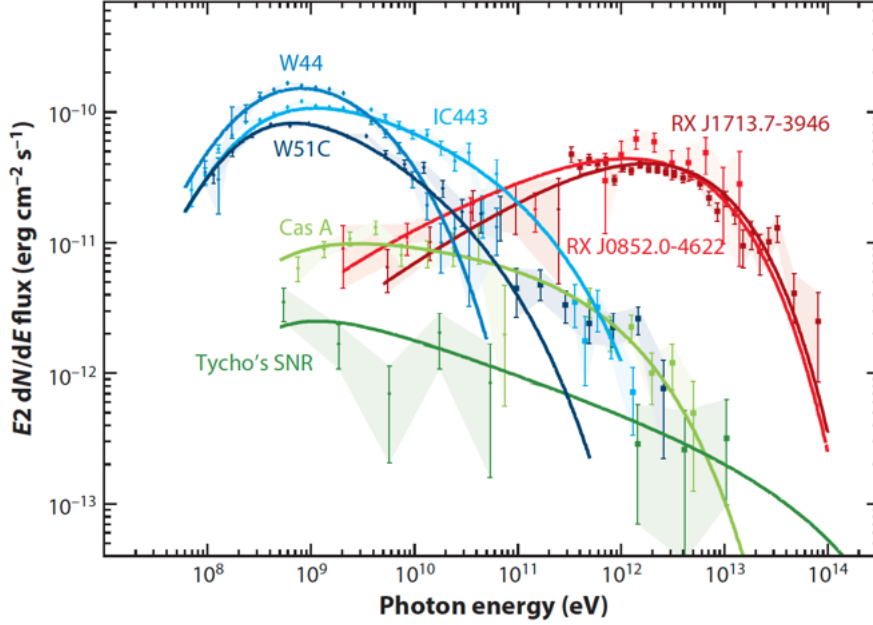


Figure 2.7: Representative gamma-ray spectra of several supernova remnants, illustrating different spectral slopes, breaks, and cutoff behaviour relevant for source interpretation. Adapted from [19].

In practice, distinguishing leptonic from hadronic gamma-ray emission is often difficult, because different particle populations and environmental conditions can produce similar gamma-ray spectra. Robust interpretation therefore requires a consistent combination of spectral shape, multi-wavelength information, source morphology, and environmental tracers such as gas density, magnetic fields, and radiation fields. Where available, neutrino observations can provide an additional constraint on hadronic scenarios [19].

Figure 2.7 demonstrates that gamma-ray sources can show very different spectral shapes. Such differences carry information about the underlying particle population and maximum acceleration energy, but they do not by themselves always provide a unique distinction between leptonic and hadronic scenarios.

For this thesis, this discussion provides the astrophysical context for the air-shower and Cherenkov-detection principles developed in the following sections.

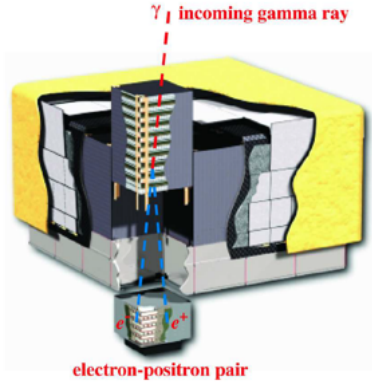
2.2.3 Detection Mechanisms

Space-Based Detectors

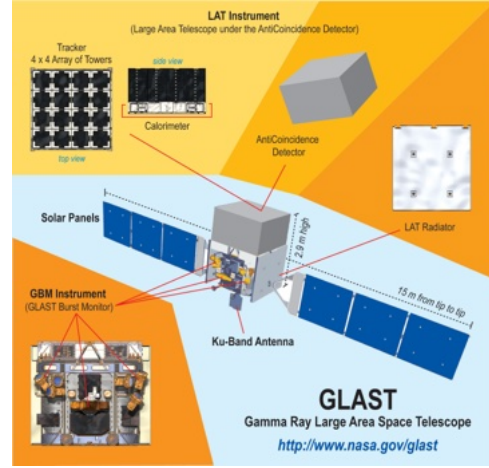
The Earth’s atmosphere is opaque to gamma rays, so direct detection requires instruments operated above the atmosphere. Space-based observatories cover the low- and intermediate-energy gamma-ray regime, from the MeV range to several hundred GeV. In this energy range, instruments such as the Fermi Large Area Telescope measure gamma rays directly inside the detector volume [13, 19].

At photon energies above roughly a few tens of MeV, modern space-based gamma-ray telescopes commonly use pair-conversion detection. An incoming gamma ray interacts with a high- Z converter material, such as tungsten, and produces an electron–positron pair. The tracks of these particles are used to reconstruct the incoming photon direction, while a calorimeter estimates the deposited energy. Since charged cosmic rays are a much larger background, an anticoincidence detector is used to reject charged-particle events. This combination of tracker, calorimeter, and anticoincidence detector forms the basic architecture of instruments such as the Fermi Large

Area Telescope [13, 35].



(a) Schematic illustration of pair-conversion detection in a space-based gamma-ray telescope.



(b) Schematic layout of the LAT instrument, showing the tracker, calorimeter, and anticoincidence detector.

Figure 2.8: Principle and instrument realization of space-based gamma-ray detection. The left panel illustrates conversion of an incoming gamma ray into an electron–positron pair, while the right panel shows the tracker, calorimeter, and anticoincidence subsystems used for event reconstruction and background rejection. Adapted from [13, 35].

Figure 2.8 illustrates the main advantage of space-based pair-conversion telescopes: the gamma ray is measured directly before it is absorbed by the atmosphere. This allows clean event reconstruction and stable calibration in the GeV energy range. The limitation is collection area. Because gamma-ray flux decreases rapidly with energy, satellite instruments become inefficient at very high energies, where much larger effective areas are required [19].

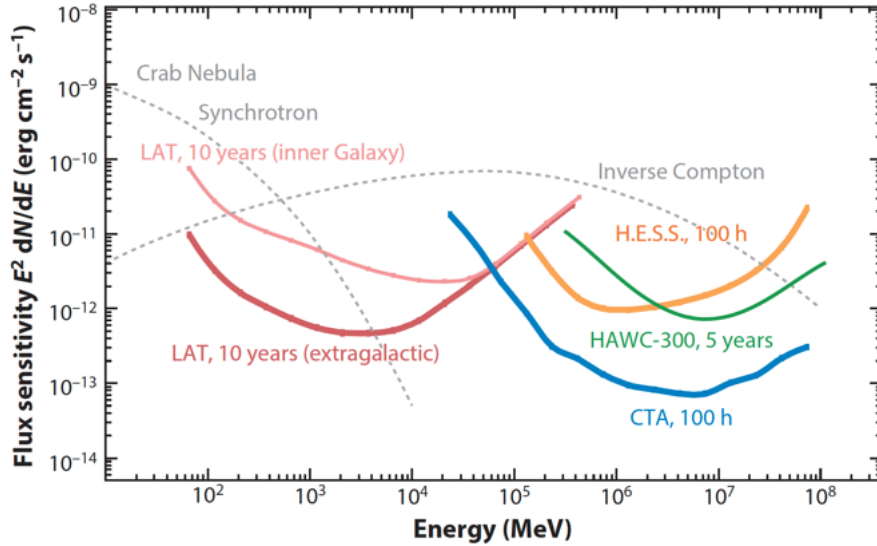


Figure 2.9: Illustrative comparison of the sensitivity ranges of space-based and ground-based gamma-ray instruments. Direct detection with Fermi-LAT dominates at lower energies, while ground-based instruments such as H.E.S.S., HAWC, and CTA become more sensitive at higher energies because atmospheric-shower detection provides much larger effective collection areas. Adapted from [19].

This complementarity is shown in Fig. 2.9. Space-based instruments define the GeV view of the gamma-ray sky, while ground-based observatories extend the accessible range into the TeV regime and beyond by using the atmosphere as part of the detector system. This transition is directly relevant for SWGO, which is designed as a ground-based water Cherenkov array for very-high-energy gamma-ray astronomy.

Ground-Based Detectors

At very high energies, gamma-ray fluxes become too low for efficient direct detection with space-based instruments. Ground-based gamma-ray astronomy therefore uses the Earth's atmosphere as part of the detector system. A primary gamma ray initiates an extensive air shower, and the event is reconstructed indirectly from the Cherenkov light and secondary particles produced in the cascade [5].

Two main ground-based techniques are relevant: imaging atmospheric Cherenkov telescopes and extensive air-shower arrays. Imaging Atmospheric Cherenkov Telescopes (IACTs) detect the short Cherenkov flashes emitted by charged shower particles in the atmosphere. Large optical reflectors focus this light onto fast pixelized cameras, allowing the shower direction, energy, and morphology to be reconstructed from the recorded image. Because several telescopes can view the same air shower from different positions, stereoscopic arrays improve angular reconstruction and background rejection [5].



Figure 2.10: The H.E.S.S. array in Namibia, consisting of multiple imaging atmospheric Cherenkov telescopes. Arrays of this type detect Cherenkov light produced by extensive air showers and reconstruct the properties of the primary gamma ray stereoscopically. Adapted from [21].

H.E.S.S., shown in Fig. 2.10, is a representative IACT array. Its multiple telescopes observe the same shower stereoscopically, while Fig. 2.11 illustrates the basic telescope structure: a large reflector, camera support, and fast imaging camera. IACTs provide excellent sensitivity and angular resolution, but they operate mainly during clear, dark nights and observe a limited field of view at a given time.

The second major technique is based on extensive air-shower (EAS) arrays. These instruments sample secondary particles that reach ground level using detector units distributed over a large area. Instead of imaging the atmospheric Cherenkov flash, EAS arrays reconstruct the event from the spatial and timing pattern of signals recorded across the detector plane. Detector elements may include scintillators or water Cherenkov detectors [5].

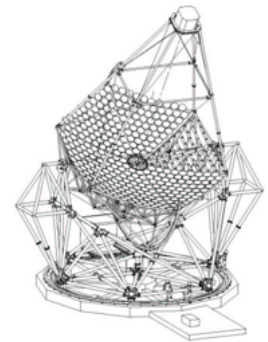


Figure 2.11: Schematic view of a large imaging atmospheric Cherenkov telescope. Adapted from [18].



Figure 2.12: The HAWC observatory in Mexico, consisting of a dense array of water Cherenkov detector tanks.[23].

HAWC, shown in Figs. 2.12 and 2.13, is a representative water Cherenkov EAS array. Its tanks record the Cherenkov light produced when charged shower particles pass through water. From the signal amplitudes and arrival times across the array, the shower direction, core position, and energy-related size can be reconstructed. Compared with IACTs, water Cherenkov arrays generally have a higher energy threshold and lower instantaneous point-source sensitivity, but they offer a very large field of view and a high duty cycle. This makes them especially useful for sky surveys, extended emission, and transient phenomena [2].

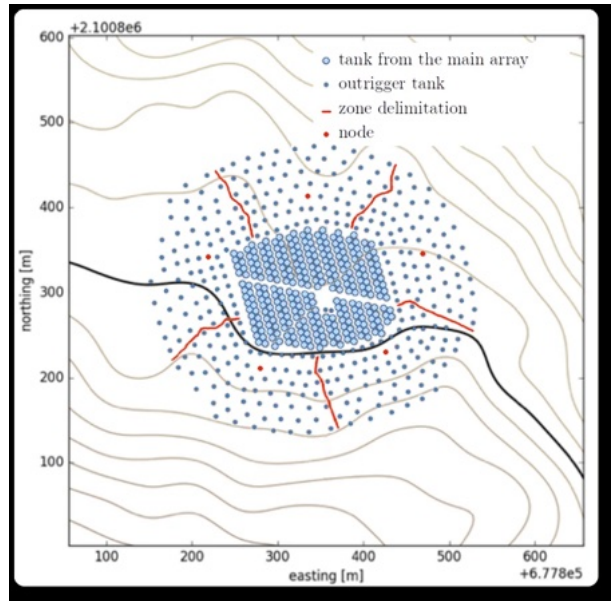


Figure 2.13: Layout of the HAWC main array and the surrounding outrigger array. Adapted from [26].

2.3 Cosmic-Ray Background and Extensive Air Showers

Ground-based gamma-ray astronomy relies on the detection of atmospheric cascades produced when high-energy particles enter the atmosphere. Although the desired signal is produced by gamma-ray-induced showers, the overwhelming majority of detected events are initiated by charged cosmic rays. The ability to distinguish these two classes of events is therefore essential. This separation is possible because electromagnetic and hadronic showers differ in their particle content, lateral structure, muon component, and detector signatures.

2.3.1 Hadronic and Electromagnetic Shower Components

When a cosmic ray, usually a proton or heavier nucleus, enters the atmosphere, its first interaction is hadronic. The resulting cascade contains a hadronic core, an electromagnetic component, and a muonic component. Secondary nucleons and mesons continue to interact with air nuclei, transferring the primary energy into different shower components. Neutral pions decay rapidly into photons, as shown in Eq. (2.2).

which feed the electromagnetic component. Charged pions can either interact further or decay into muons and neutrinos,

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad (2.3)$$

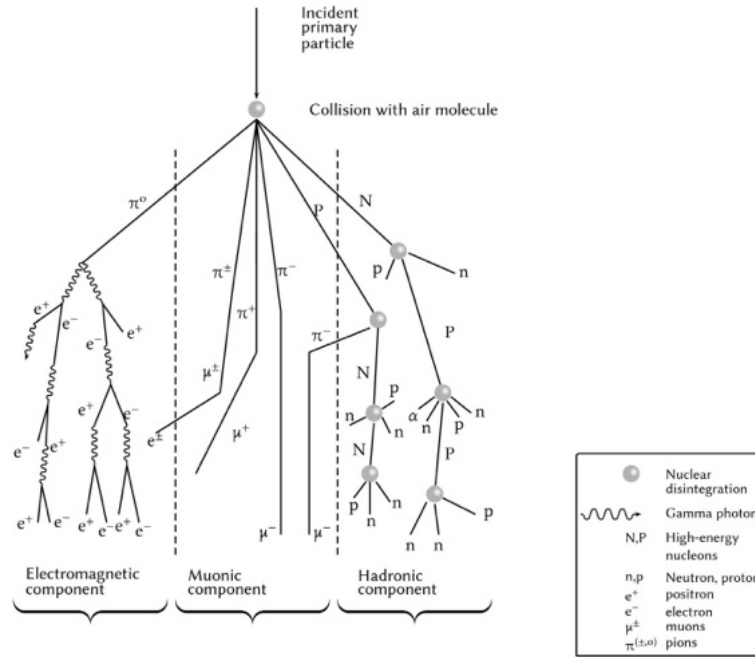


Figure 2.14: Basic scheme of an extensive air shower, showing electromagnetic, muonic, and hadronic components. Adapted from [14].

thereby generating the penetrating muonic component. A hadron-induced shower is therefore a mixed cascade in which hadronic interactions continuously feed electromagnetic and muonic subcomponents [19].

A gamma-ray-induced shower is simpler in composition. Its dominant interaction sequence is electromagnetic: pair production,

$$\gamma \rightarrow e^+ + e^-, \quad (2.4)$$

followed by bremsstrahlung emission,

$$e^{\pm} \rightarrow e^{\pm} + \gamma. \quad (2.5)$$

The emitted photons can again undergo pair production, producing the repeated pair-production–bremsstrahlung cycle characteristic of an electromagnetic shower. The resulting cascade is composed mainly of electrons, positrons, and photons, with a much smaller muonic component than in hadron-induced showers [5, 19].

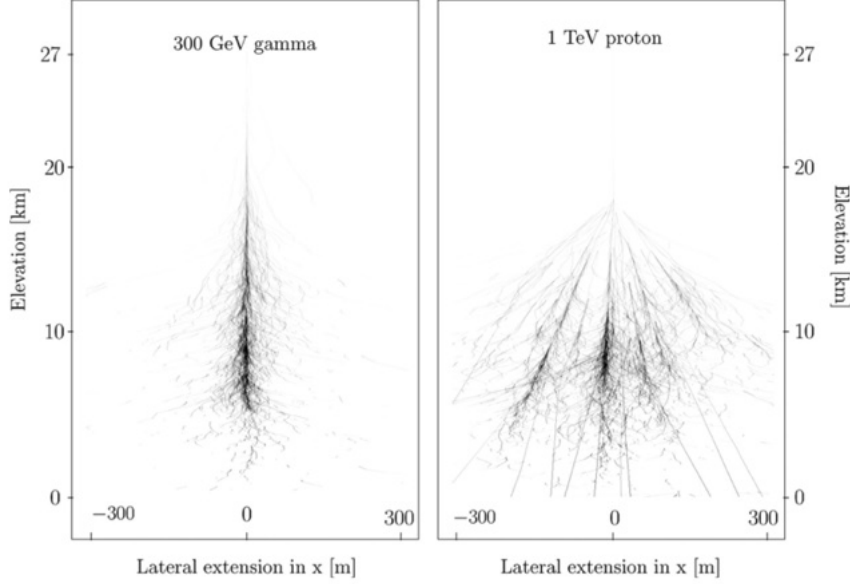


Figure 2.15: Comparison of the atmospheric development of a gamma-ray-induced and a proton-induced extensive air shower. The gamma-ray shower (300 GeV, left) develops as a comparatively compact electromagnetic cascade, whereas the proton shower (1 TeV, right) shows a broader and more irregular structure due to additional hadronic and muonic components. Adapted from [5].

The difference in particle content is the physical basis for gamma–hadron separation. Gamma-ray showers are primarily electromagnetic and tend to produce smoother and more compact footprints at ground level. Hadron-induced showers contain additional muons and hadronic substructures, leading to larger fluctuations and more irregular detector patterns. The WCD observables used to exploit this difference are discussed later in Sec. 2.5.

2.3.2 Electromagnetic Shower Development

The longitudinal development of a gamma-ray-induced shower can be understood with the Heitler model. In this simplified picture, the cascade is represented as a sequence of discrete branchings with approximately equal energy sharing between daughter particles. Although idealized, the model captures the basic scaling of particle multiplication and the formation of a shower maximum [19].

In atmospheric shower physics, the propagation depth is commonly described by the slant depth

$$X = \int \rho(s) ds, \quad (2.6)$$

where $\rho(s)$ is the atmospheric density along the shower path. The characteristic scale for electromagnetic interactions is the radiation length X_0 , approximately 37 g cm^{-2} in air [19].

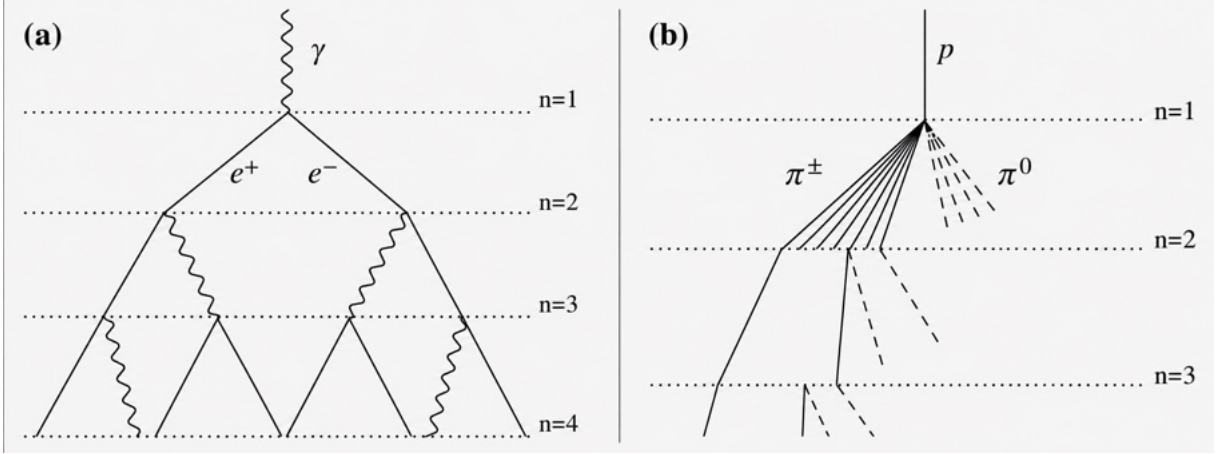


Figure 2.16: Schematic illustration of the Heitler model for an electromagnetic air shower. Adapted from [33].

The cascade grows until the average particle energy drops to the critical energy E_c . Below this energy, ionization losses dominate over further radiative multiplication, and the number of shower particles begins to decrease. The point of maximum particle number defines the shower maximum. In air, the critical energy is of order 85 MeV [19].

Within the Heitler approximation, the depth of the shower maximum is

$$X_{\max} \approx X_0 \ln \left(\frac{E_0}{E_c} \right), \quad (2.7)$$

where E_0 is the primary gamma-ray energy. This relation shows that the shower maximum moves deeper into the atmosphere only logarithmically with energy. High-altitude ground-based observatories are therefore advantageous because they are located closer to the region where many secondary particles and strong Cherenkov emission are still present [19].

2.3.3 Lateral Structure of the Shower

An electromagnetic shower also develops a finite lateral spread around its main axis. This spread is caused mainly by multiple Coulomb scattering of secondary electrons and positrons, together with the finite opening angles introduced by pair production and bremsstrahlung. The shower is therefore not a one-dimensional cascade, but an extended particle distribution in the atmosphere [19].

This behaviour is illustrated in Fig. 2.17. The left panel shows the idealized Heitler picture, while the right panel shows a simulated 100 GeV photon-induced shower. The simulation highlights that most particles remain close to the shower axis, but that the cascade still occupies a finite atmospheric volume.

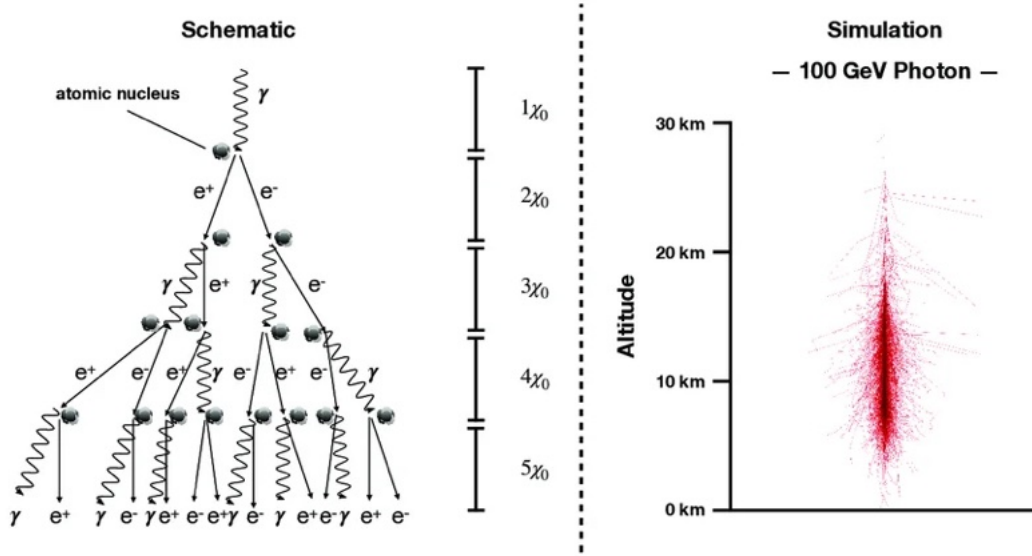


Figure 2.17: Illustration of the development of an electromagnetic air shower. The left panel shows a schematic Heitler-type picture of repeated pair production and bremsstrahlung, while the right panel shows a simulated 100 GeV photon-induced shower in the atmosphere. The figure illustrates both the longitudinal growth of the cascade and its finite lateral spread around the shower axis. Adapted from [47].

The lateral structure determines how secondary particles and Cherenkov light are distributed at observation level. In a detector array, the shower footprint is sampled from this distribution by individual detector units. Its practical use for shower reconstruction and gamma–hadron separation is discussed in Sec. 2.5.

2.4 Cherenkov Radiation

Cherenkov radiation is produced when a charged particle passes through a transparent medium faster than light can propagate in that medium. Although the particle does not exceed the speed of light in vacuum, it can move faster than the local phase velocity of light, c/n , where n is the refractive index of the medium. Under this condition, the electromagnetic disturbance caused by the moving charge adds coherently and forms a characteristic cone of light [20].

The condition for Cherenkov emission is

$$\beta n > 1, \quad (2.8)$$

where $\beta = v/c$ describes the particle velocity relative to the speed of light in vacuum. This makes Cherenkov radiation a threshold process: particles below this velocity do not induce Cherenkov light, while sufficiently relativistic charged particles do. Once the threshold is exceeded, the induced light is concentrated on a cone around the particle direction. The opening angle θ_C is given by

$$\cos \theta_C = \frac{1}{\beta n}. \quad (2.9)$$

For highly relativistic particles, where $\beta \approx 1$, the Cherenkov angle is mainly determined by the refractive index of the medium. In air, where the refractive index is only slightly larger than

unity, the angle is small and typically of the order of 1° or less. In water, the larger refractive index leads to a much wider cone, with an angle of about 42° for relativistic particles [28].

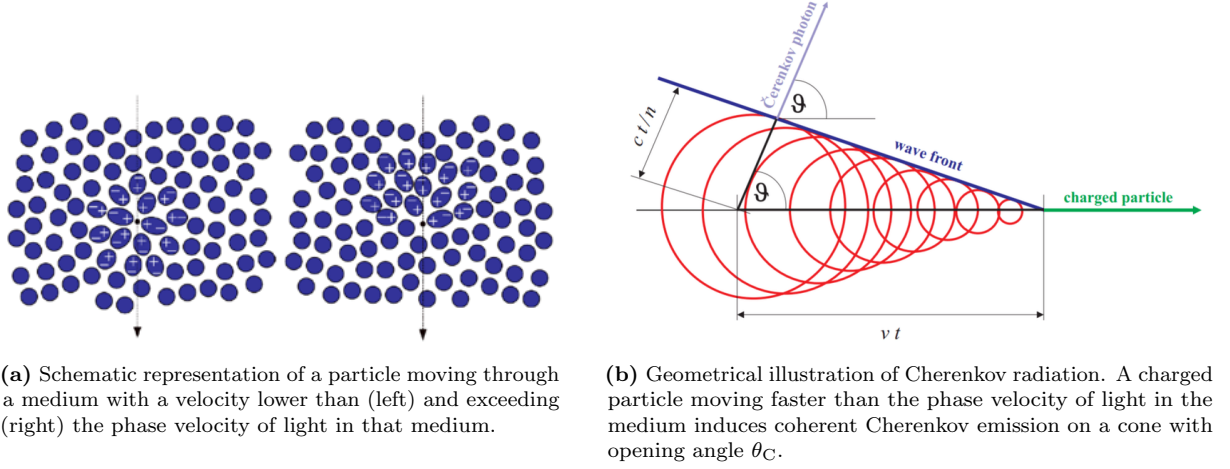


Figure 2.18: Basic principle and geometry of Cherenkov radiation. Panel (a) illustrates the threshold behaviour of Cherenkov emission, while panel (b) shows the conical wavefront induced in a transparent medium by a charged particle travelling faster than the phase velocity of light in that medium. Panel (a) adapted from Leitl [31]; panel (b) adapted from [39].

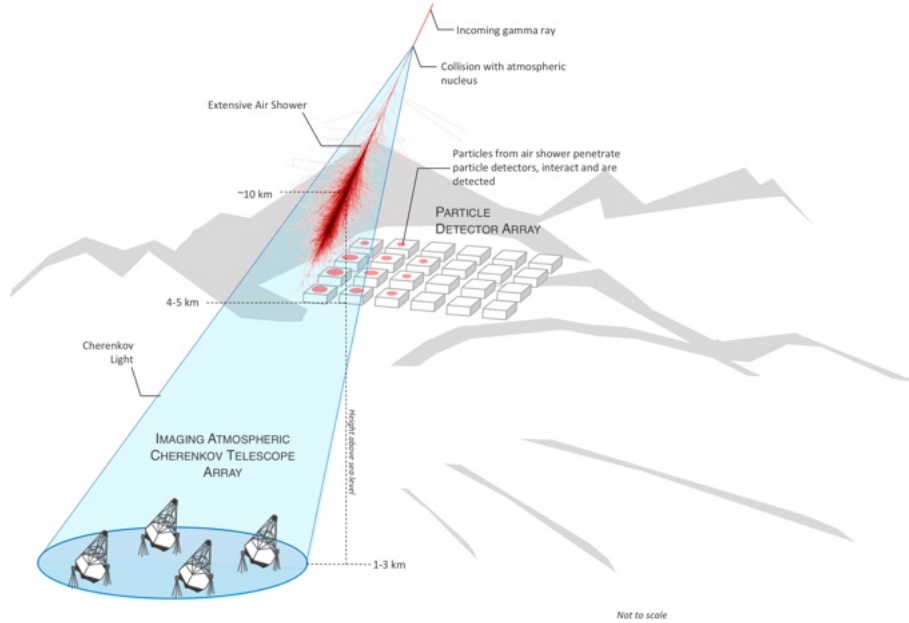


Figure 2.19: Schematic illustration of Cherenkov-light production in an extensive air shower and its detection from the ground. A primary gamma ray initiates an atmospheric cascade at high altitude. Relativistic charged particles in the shower induce Cherenkov emission in the atmosphere, while surviving secondary particles can also be sampled by ground-based particle-detector arrays. Adapted from [50].

The light produced through this process is prompt and is mainly concentrated in the near-ultraviolet and blue part of the spectrum. Since the light is produced almost instantaneously and with a well-defined geometry, its arrival time, intensity, and spatial distribution can be used to infer the properties of the charged particles that produced it [19].

In gamma-ray astronomy, Cherenkov radiation is used in two closely related ways. Imaging atmospheric Cherenkov telescopes detect the short optical flash produced in the atmosphere by relativistic electrons and positrons in an extensive air shower. Water Cherenkov detectors, such as those used in HAWC, LHAASO, and proposed for SWGO, rely on the same physical principle

inside water-filled detector units. In this case, secondary shower particles enter the water and induce Cherenkov emission, which is then recorded by photomultiplier tubes [46].

Thus, Cherenkov radiation provides a common detection principle for several ground-based techniques. Whether the light is produced in air, water, or another transparent medium, it carries information about the number, timing, direction, and energy deposition of relativistic charged particles. These quantities are central to the reconstruction of gamma-ray and cosmic-ray events [19].

2.4.1 Cherenkov Light Detection in Water Cherenkov Tanks

In water Cherenkov detector arrays, the Cherenkov signal is produced inside water-filled detector units rather than collected directly from the atmosphere. When secondary particles from an extensive air shower reach the ground, they enter the water volume and induce Cherenkov light if their velocity exceeds the phase velocity of light in water. The tank therefore acts as a local sampling detector: it converts the passage of shower particles into optical photons, which are detected by photomultiplier tubes [19].

The working principle is illustrated in Fig. 2.20. In the HAWC design, each water Cherenkov detector consists of a large light-tight tank filled with purified water, with photomultiplier tubes mounted at the bottom. Charged shower particles crossing the water induce Cherenkov photon emission along their path. Some photons reach the PMTs directly, while others arrive after reflections or scattering inside the tank. The resulting PMT signals provide two basic observables: the amount of detected light, usually expressed in photoelectrons, and the arrival time of the signal [1].

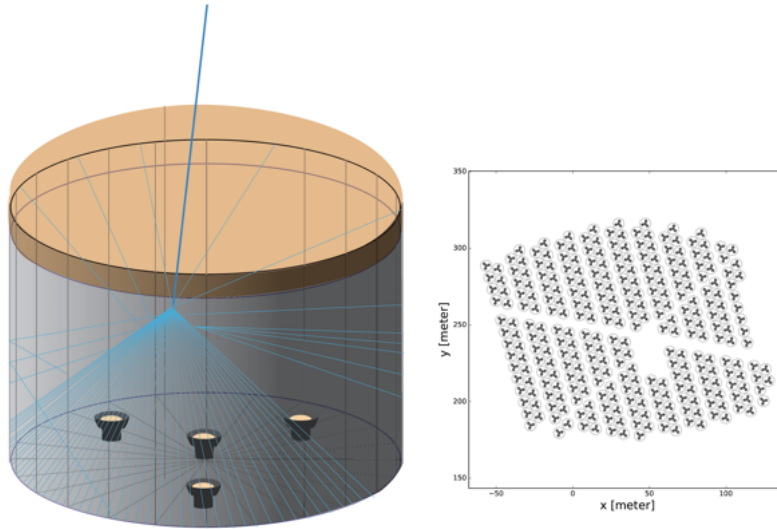


Figure 2.20: Principle and array layout of the HAWC water Cherenkov detector. The left panel shows a single water Cherenkov detector unit, where secondary air-shower particles entering the tank induce Cherenkov light in water that is recorded by photomultiplier tubes at the bottom. The right panel shows the arrangement of many such detector units in the HAWC array. Adapted from [1].

Across a WCD array, many detector units sample the shower footprint at different positions on the ground. The measured charge gives information on the local particle density, while the signal timing records the passage of the shower front across the array. These two quantities form the basis for event reconstruction and event identification, which are discussed in more detail in Sec. 2.5.

2.5 Air-Shower Detection and Event Identification

Once an extensive air shower has been sampled by a ground-based detector, the recorded signals must be converted into physically useful information. In a water Cherenkov detector (WCD) array, this involves two closely connected tasks: identifying whether an event is more likely to be gamma-ray- or hadron-induced, and reconstructing the main properties of the primary particle, such as its core position, arrival direction, and energy-related shower size.

2.5.1 Gamma–Hadron Separation in WCD Arrays

A central challenge in ground-based gamma-ray astronomy is that most detected air showers are produced by charged cosmic rays rather than by gamma rays. In a WCD array, hadron-induced showers therefore form the dominant background, while gamma-ray-induced showers are the comparatively rare signal. Gamma–hadron separation is therefore essential for extracting astrophysical gamma-ray events from the much larger cosmic-ray event sample [19].

The separation relies on the different ground-level structure of the two shower types. Gamma-ray showers are mainly electromagnetic and tend to produce smoother, more compact signal patterns. Hadron-induced showers contain additional muons and hadronic substructures, which often lead to stronger fluctuations and isolated high-charge signals away from the shower core [46].

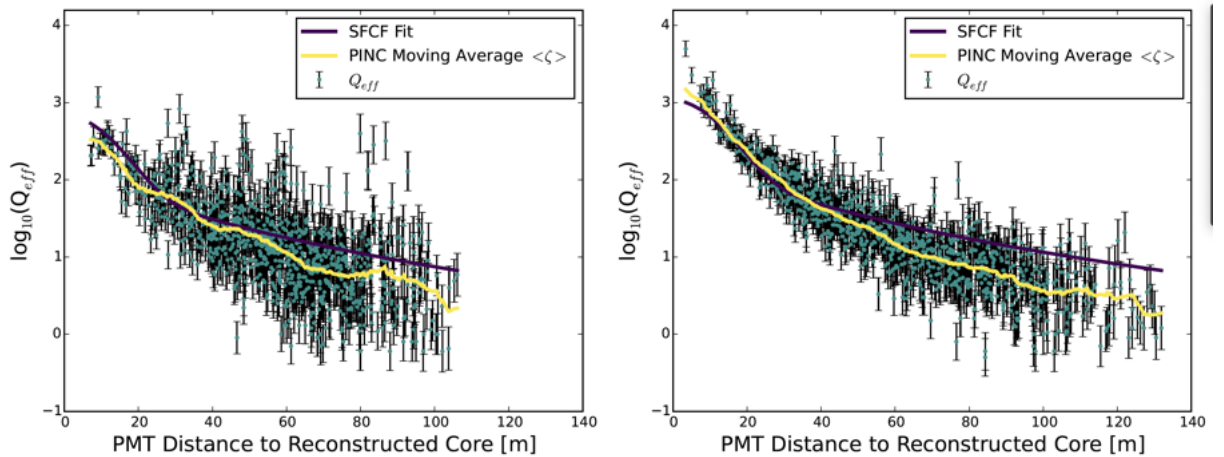


Figure 2.21: Comparison of lateral signal distributions for a hadron-induced air shower and a gamma-ray candidate recorded with HAWC. The left panel shows a cosmic-ray event with isolated high-charge hits away from the reconstructed shower core, while the right panel shows a gamma-ray candidate with a smoother lateral distribution. These differences in the charge pattern are used for gamma–hadron separation in water Cherenkov detector arrays. Adapted from [1].

Figure 2.21 illustrates this principle using HAWC events. The hadronic event contains high-charge points far from the core, while the gamma-ray candidate follows a smoother lateral trend. Thus, the array does not only measure the total amount of detected light, but also how regularly that light is distributed across the detector plane.

Muon content provides one of the strongest handles for this classification. Hadronic showers produce more muons than gamma-ray showers, and these penetrating particles can generate clear Cherenkov signals in water. This motivates detector concepts that enhance muon tagging, including double-layer WCD designs in which the lower chamber is used to improve sensitivity to penetrating muons [29]. Muon tagging therefore links detector geometry, light collection, charge calibration, and timing precision directly to gamma–hadron separation in double-layer WCD arrays.

2.5.2 Shower Reconstruction in WCD Arrays

After an event has been classified, the properties of the primary particle must be reconstructed from the detector response. In a WCD array, the primary gamma ray is not observed directly. Instead, the reconstruction is based on the secondary particles that reach the ground and produce Cherenkov light inside the water tanks. The PMTs record this light as charge and timing information, from which the shower core, arrival direction, and energy-related shower size are estimated [1].

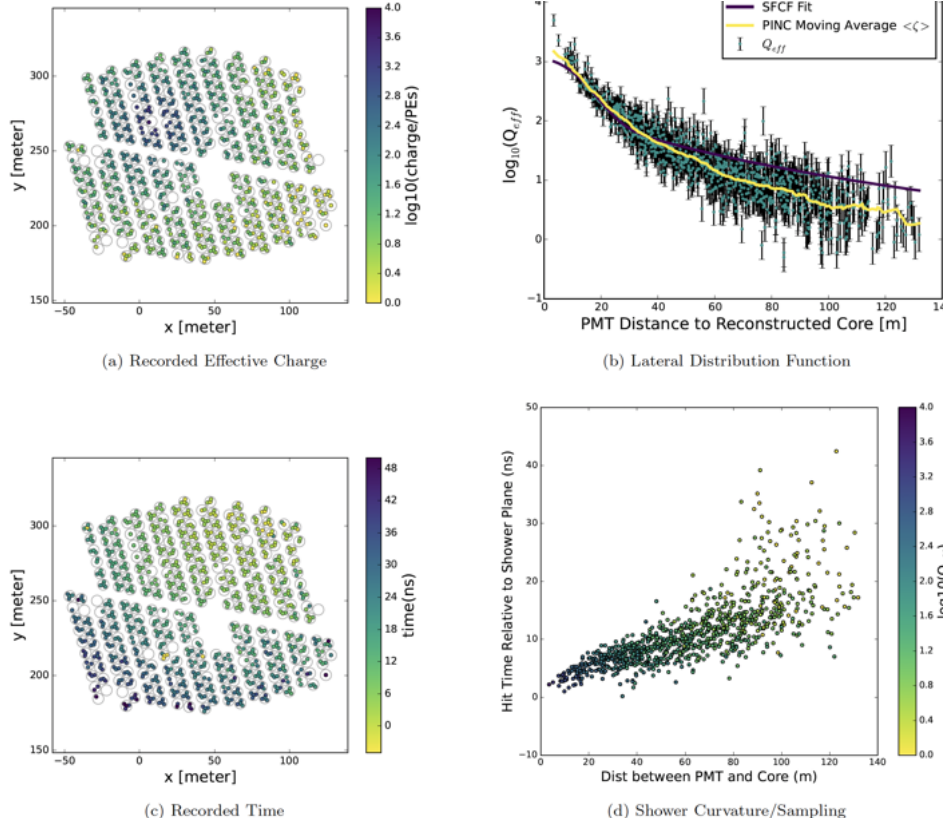


Figure 2.22: Example of HAWC shower reconstruction for a gamma-ray candidate from the Crab Nebula. The panels show the recorded PMT charge, the lateral charge distribution, the recorded hit times, and the shower-front curvature used in reconstruction. Adapted from [1].

The reconstruction logic is shown in Fig. 2.22. The charge pattern identifies where the shower deposited the strongest signal and is used to estimate the shower core and lateral distribution. The timing pattern records how the shower front crosses the array and is used to reconstruct the arrival direction. Corrections for shower-front curvature improve this directional reconstruction, especially for particles arriving farther from the core [1].

Each detector unit contributes a local measurement of signal size and arrival time. The quality of the final reconstruction therefore depends on how accurately the detector measures Cherenkov light intensity and timing [46].

If the PMT response changes because of reduced quantum efficiency, unstable gain, increased dark noise, or degraded timing behaviour, the measured charge and time distributions can also change. Such effects may propagate into the reconstructed shower core, arrival direction, energy estimate, and gamma-hadron separation. PMT performance is therefore part of the reconstruction chain, not merely a sensor-level detail.

2.6 Role of Photon Detection in WCD Performance

The previous sections showed that WCD arrays infer air-shower properties from the amount of Cherenkov light detected and the time at which this light is recorded. At the detector level, these observables depend on the conversion of Cherenkov photons into measurable photoelectrons. Photon detection therefore provides the direct link between the physical shower front and the charge and timing information used for event reconstruction [46].

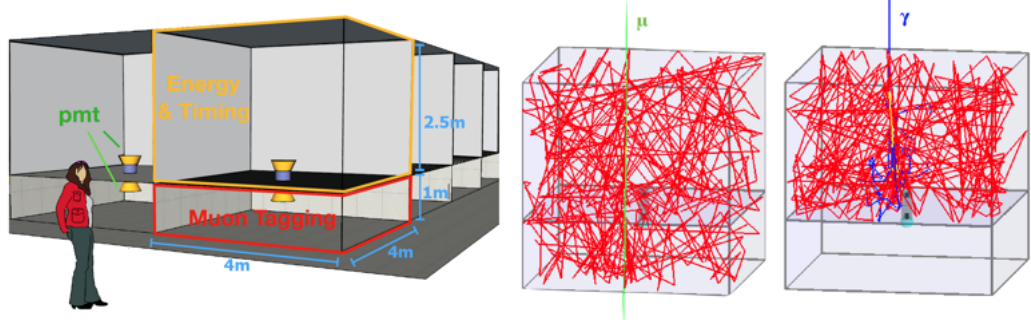


Figure 2.23: Illustration of a double-layer water Cherenkov detector concept for gamma-ray astronomy. The figure indicates the PMT-instrumented water volumes in which Cherenkov light is converted into measurable detector signals. The detector geometry and the response of the upper and lower chambers are discussed in Sec. 3.3.2. Adapted from [29].

The number of photoelectrons available for charge and timing reconstruction depends directly on the spectral overlap between the Cherenkov photon field and the PMT quantum efficiency. Characterizing the present wavelength-dependent and spatial QE response of the extracted ANTARES PMTs is therefore directly relevant to their potential use as photosensors in a water Cherenkov detector.

Chapter 3

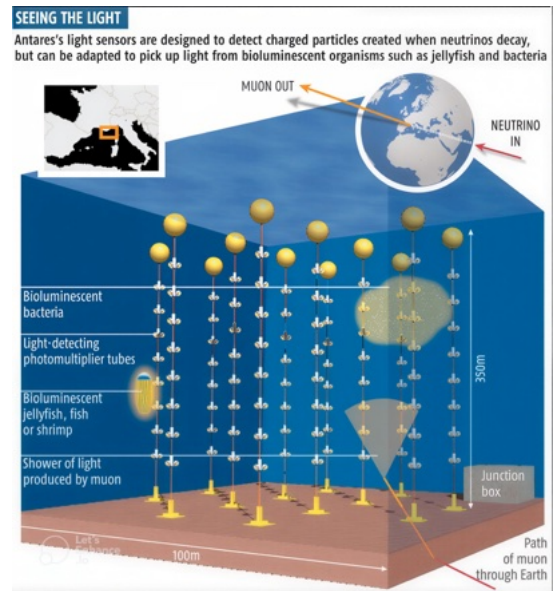
Legacy & Future: ANTARES & SWGO

3.1 ANTARES Experiment

The ANTARES experiment was a deep-sea neutrino telescope designed to detect high-energy neutrinos through the Cherenkov light emitted by relativistic charged particles in water. Its scientific motivation was based on the use of neutrinos as cosmic messengers: unlike charged cosmic rays, neutrinos are not deflected by magnetic fields, and unlike photons, they can escape dense astrophysical environments that may be opaque to electromagnetic radiation. ANTARES therefore provided a way to probe the high-energy non-thermal Universe from the Northern Hemisphere using a messenger that preserves directional information over cosmological distances [4].



(a) Example of an ANTARES storey during deployment, showing optical modules mounted on the mechanical support structure.



(b) Schematic illustration of the ANTARES detection principle and detector layout.

Figure 3.1: Visual overview of the ANTARES experiment. Panel (a) shows detector hardware during deployment, including optical modules mounted on a storey structure. Panel (b) illustrates the deep-sea detection concept: a high-energy neutrino can interact near the detector and produce a relativistic muon whose Cherenkov light is recorded by optical sensors along vertical detection lines. Panel (b) adapted from [37].

ANTARES was deployed in the Mediterranean Sea, about 40 km offshore from Toulon, at a

depth of approximately 2475 m. In its final configuration, the detector consisted of 12 vertical detection lines anchored to the seabed. These lines instrumented a large water volume with a sparse three-dimensional arrangement of optical modules, as illustrated in Fig. 3.1 [4].

The detector was optimized mainly for the muon channel. A neutrino interacting near the detector can produce a high-energy muon, which then travels through water and emits Cherenkov radiation. By measuring the arrival times and amplitudes of the light recorded by different optical modules, ANTARES reconstructed the muon trajectory and inferred the direction of the parent neutrino. This approach allowed the detector to search for astrophysical neutrino sources with good directional precision [4].

The deep-sea environment imposed several technical constraints for the detector. The optical modules had to operate under high pressure, remain stable over long periods, and distinguish rare Cherenkov signals from natural optical backgrounds such as bioluminescence and radioactive decays in seawater. The deployment image in Fig. 3.1a highlights this hardware context: optical detection, mechanical support, pressure tolerance, readout integration, and long-term subsea operation had to be realized together in a deployable system [4].

For the present thesis, ANTARES is relevant not only as a completed neutrino telescope, but also as the source of the photomultiplier tubes investigated for possible reuse in SWGO. After long-term deployment, decommissioning, recovery, and extraction, these PMTs form a legacy sensor population whose present quantum-efficiency response can be assessed experimentally. The key question is therefore whether sensors originally developed for deep-sea Cherenkov detection still retain sufficient photon-detection capability for a possible second application in a future water Cherenkov gamma-ray observatory.

3.1.1 Detector and Optical Module Overview

Beyond the basic detection concept, the ANTARES architecture was shaped by the practical demands of deep-sea operation. Optical sensing, mechanical support, positioning, power delivery, timing distribution, and data transmission all had to function reliably over large distances and under long-term immersion conditions [4].

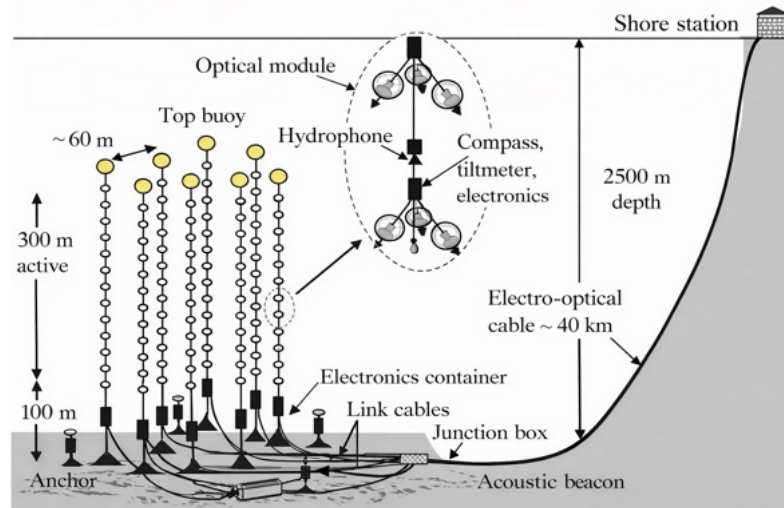


Figure 3.2: Schematic layout of the ANTARES detector, showing the line-based architecture, the vertical arrangement of optical modules on storeys, the seabed anchoring and junction-box infrastructure, and the electro-optical connection to the shore station. Adapted from [4].

Figure 3.2 shows the hierarchical layout of ANTARES. The detector was connected to the shore station by an electro-optical cable of about 40 km length and consisted of vertical detection lines

anchored to the seabed. In its final configuration, ANTARES used 12 lines, spaced by roughly 60 m, each carrying a sequence of storeys along an instrumented height of about 300 m. This sparse three-dimensional structure allowed the detector to sample Cherenkov light from charged particles crossing the surrounding water volume [4].

In this architecture, each detection line was divided into storeys, which served as local optical-sensing units. Each storey grouped optical modules with local electronics and auxiliary instrumentation, forming a local sensing node on a detection line. For the present thesis, this hierarchy is important because it shows that the investigated PMTs originated from complete ANTARES optical modules embedded in a full deep-sea detector system, rather than from standalone laboratory devices.

3.1.2 Storey and Optical Module Architecture

A local view of the ANTARES storey and optical-module structure is shown in Fig. 3.3. The figure illustrates how optical modules were mounted around the local control module, together with auxiliary instrumentation used for positioning and environmental monitoring. These additional devices were essential for ANTARES operation, but their main relevance here is to define the original detector environment of the recovered PMTs [4].

The optical module is the component most directly relevant for this thesis. As shown in the inset of Fig. 3.3, each module contained a large-area photomultiplier tube inside a pressure-resistant glass sphere. Transparent optical gel provided optical coupling between the PMT window and the sphere while also supporting the tube mechanically. An internal LED was included for calibration and monitoring [11].

This construction was necessary because the modules operated at a depth of approximately 2500 m, where the hydrostatic pressure reaches several hundred bar. The optical module therefore formed the complete interface between Cherenkov light in seawater and the electronic readout of the ANTARES detector.

This context is essential for the reuse question. The PMTs studied in this thesis were recovered from integrated deep-sea optical modules after long-term operation, extraction, cleaning, and storage. Their measured quantum-efficiency response must therefore be interpreted in light of both their operational history and their mechanical extraction from the original optical-module environment.

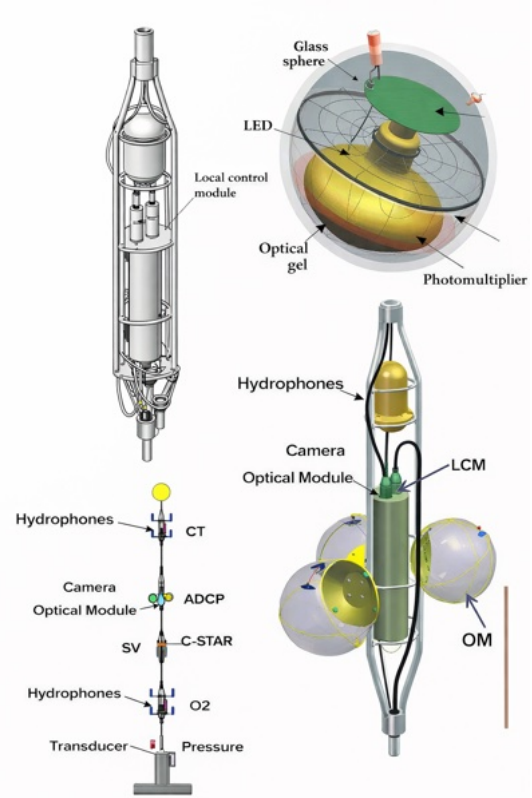


Figure 3.3: Local ANTARES detector elements, showing the storey-level arrangement of optical modules around the local control module and the internal structure of an optical module. Adapted from [4] and [11].

3.2 ANTARES Photomultiplier Extraction

The ANTARES PMTs used in this study were not unused laboratory devices, but components recovered from previously deployed optical modules. Their reuse therefore required a dedicated

extraction procedure in which the original deep-sea module was opened, the photomultiplier was released from the glass housing and optical gel, and the tube was cleaned and transferred to storage. Thus, the extracted PMTs must be interpreted as recovered detector components with both a long-term operational history in ANTARES and an additional handling history from recovery, extraction, cleaning, and storage [34].

The extraction procedure developed at ECAP was established for the recovery of the 10” ANTARES photomultipliers from their original optical modules. By April 2026, it had already been applied to more than 140 PMTs. The process was non-trivial because each PMT was embedded in an integrated optical module containing a pressure-resistant glass sphere, optical gel, internal wiring, and mechanical support elements. These components had originally been designed for long-term deep-sea operation, not for later recovery [34].



Figure 3.4: Opening sequence of an ANTARES optical module during PMT extraction. The module is mechanically opened, vented and separated into hemispheres, and the internal connections are removed while preserving PMT traceability. Adapted from [34].

The first stage of the procedure was the opening of the optical module, shown in Fig. 3.4. After stabilizing the module, the external collar and sealing material were removed, the vacuum seal was released, and the two glass hemispheres were separated. Internal electrical connections were then disconnected, and the optical-module and PMT identifiers were documented to preserve traceability between the recovered tube and its original ANTARES hardware position [34].

After opening, the PMT remained fixed inside the transparent front hemisphere by the surrounding cage and optical gel. The release step therefore required removal of the cage elements and controlled cutting of the gel around the PMT. This was one of the most delicate parts of the extraction, because the gel had to be separated from the glass housing without allowing the cutting tools to contact or damage the PMT surface [34].

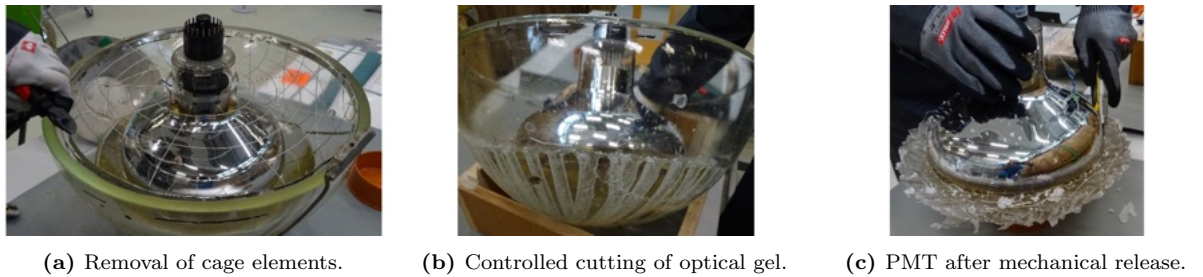


Figure 3.5: Mechanical release of the ANTARES photomultiplier from the front hemisphere of the optical module. After removal of cage elements, the optical gel is cut in controlled passes until the PMT can be separated from the glass housing. Adapted from [34].

Once released, residual optical gel still remained on the PMT surface. This material was removed in several stages: larger gel regions were first removed mechanically, the remaining layer was reduced carefully from the glass surface, and final cleaning was performed using solvent- (Digesil - Silicon Remover Solvent) gel removal followed by isopropyl-alcohol cleaning. The aim was to obtain a clean optical surface while minimizing the risk of scratches or chemical residue that

could affect later optical measurements [34].

The extraction note also reports that PMTs corresponding to two ANTARES lines had been extracted locally at ECAP and transferred to dark storage by January 2026. Preliminary checks indicated that essentially all extracted PMTs remained functional, although reduced gain performance was observed in some cases. A small number of modules could not be processed successfully because of strongly degraded gel or water ingress. These observations are relevant because they show that the recovered population was broadly usable, but not equivalent to a set of new, unused sensors [34].



Figure 3.6: Post-release cleaning and storage of extracted ANTARES photomultipliers. Residual optical gel is removed mechanically and chemically before the recovered PMTs are transferred to dark storage. Adapted from [34].

From the perspective of this thesis, the extraction procedure defines the provenance of the PMT sample. The measured quantum-efficiency response must therefore be interpreted in light of both the long-term deep-sea operation of the tubes and the multi-stage recovery process used to remove them from their original optical modules. Extraction is therefore part of the experimental context of the reused ANTARES PMTs, not merely a preparatory handling step [34].

3.3 SWGO: Southern Wide-field Gamma-ray Observatory

The Southern Wide-field Gamma-ray Observatory (SWGO) is a next-generation ground-based gamma-ray instrument designed to observe VHE gamma rays through the detection of extensive air showers. It is conceived as a wide-field survey observatory, continuously monitoring a large fraction of the sky and recording secondary particles produced when primary gamma rays interact in the atmosphere. Its expected sensitivity and sky coverage are shown in Fig. 3.7.

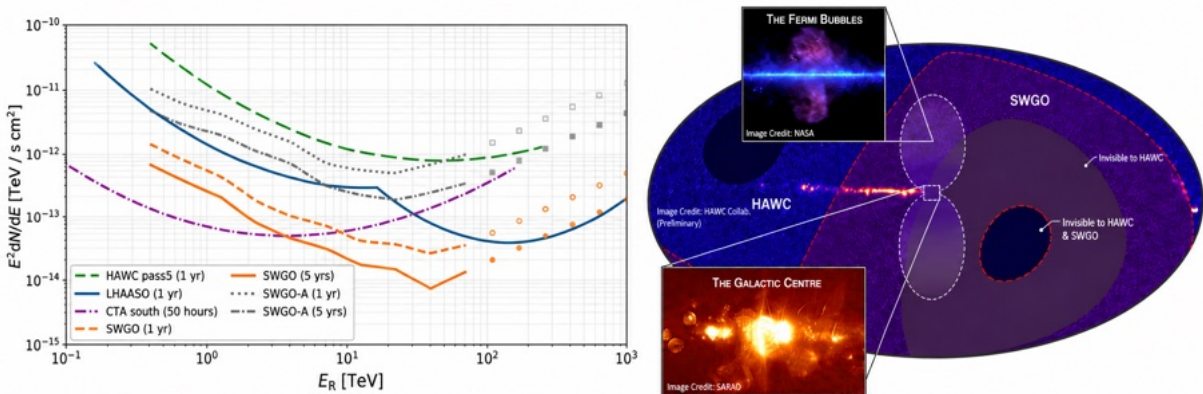


Figure 3.7: Left: Differential point-source sensitivity of SWGO compared to existing and planned instruments. Right: Expected sky coverage in Galactic coordinates. Adapted [3] [25].

The scientific motivation for SWGO arises from the current imbalance in observational capabilities between the Northern and Southern hemispheres. Existing wide-field instruments, such as HAWC,

have demonstrated the importance of continuous monitoring for extended sources and transient phenomena. However, comparable coverage of the southern sky is currently lacking. SWGO is therefore designed to provide sustained access to key astrophysical regions, most notably the Galactic Centre and the inner Milky Way, while operating with a near-continuous duty cycle [25].

Unlike imaging atmospheric Cherenkov telescopes, which provide high instantaneous sensitivity but are limited in duty cycle and field of view, SWGO records air showers over a large sky fraction continuously. This enables simultaneous monitoring of multiple sources and preserves time-domain information, making the instrument particularly suitable for transient detection and studies of extended emission. The performance shown in Fig. 3.7 reflects this complementary role, where survey capability is achieved across a broad energy range.

SWGO is expected to operate from the sub-TeV regime up to beyond 100 TeV, thereby bridging the gap between satellite-based detectors and pointed ground-based instruments while extending sensitivity toward the highest observable gamma-ray energies [25].

For this thesis, the relevant aspects of SWGO are its candidate site, array layout, and PMT-instrumented double-layer detector-unit design. These features define the detector context in which recovered ANTARES PMTs may be considered for reuse.

3.3.1 Array Layout and Site Characteristics

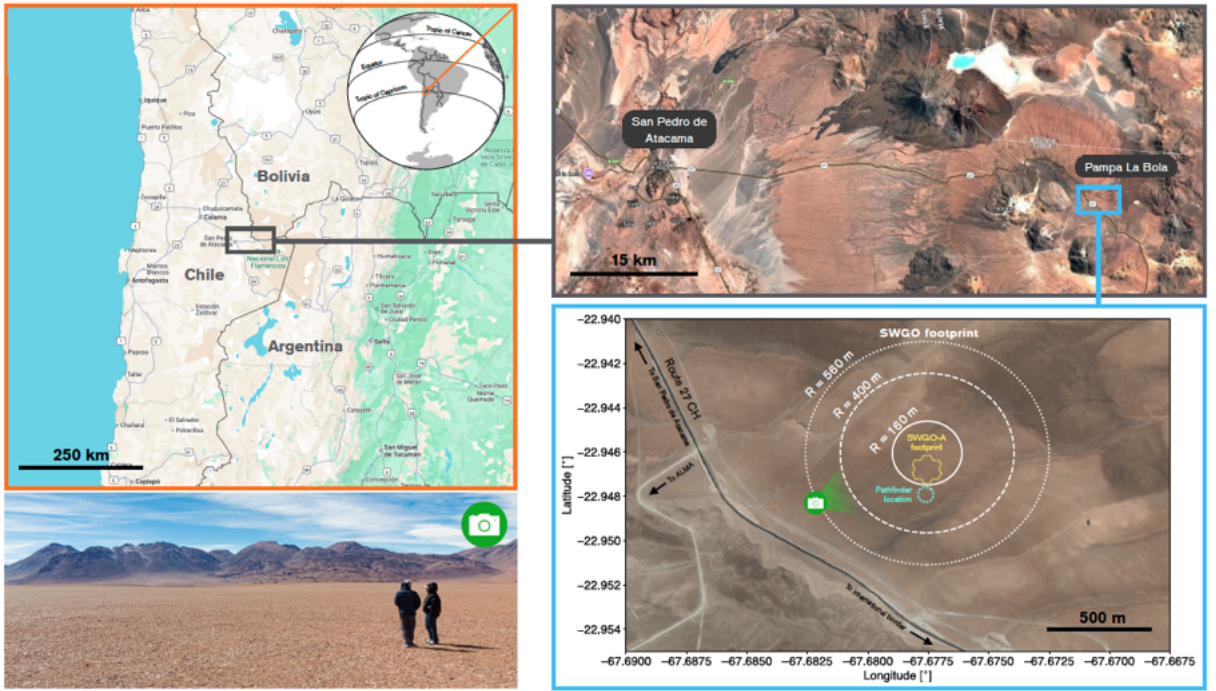


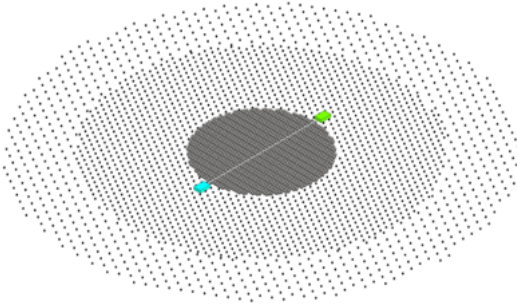
Figure 3.8: Geographic location of the SWGO candidate site in northern Chile, with a detailed view of the Pampa La Bola region and example detector footprint. Adapted from [3].

The performance of SWGO is strongly influenced by both the detector layout and its geographical location. Pampa La Bola in northern Chile, situated at an altitude of approximately 4770 m, has been selected as the preferred site, and construction planning for the array is now underway [3]. At these altitudes, the detector is positioned closer to the maximum development of extensive air showers, where the particle density is highest. This increase the number of detectable secondary particles, and therefore improve the reconstruction quality and lowers the effective energy threshold of the instrument [25].

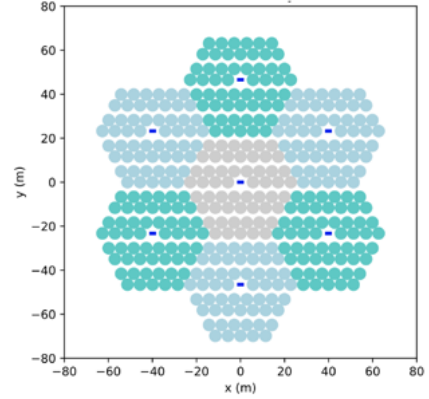
The choice of site is not only driven by altitude but also by environmental and logistical

considerations. The Atacama region offers extremely low atmospheric humidity, minimal cloud coverage, and low light pollution, ensuring stable operating conditions and high data quality. In addition, the proximity to existing astronomical infrastructure in northern Chile provides practical advantages for its deployment, maintenance, and long-term operation [25].

The baseline detector design consists of a dense inner array surrounded by a progressively sparser outer region. This configuration is motivated by the energy-dependent structure of air showers. Low-energy showers produce relatively few secondary particles, therefore requiring dense detector spacing to ensure sufficient sampling. In contrast, high-energy showers spread over larger areas and can be reconstructed with a sparser detector distribution. The combination of these regions allows SWGO to achieve sensitivity across a broad energy range, from the sub-TeV regime to beyond 100 TeV, without excessive scaling in detector cost [46].



(a) Baseline SWGO array layout with dense inner region and extended outer array.



(b) SWGO-A reference layout illustrating a compact high-density core.

Figure 3.9: Conceptual layouts of the SWGO detector. The baseline design (a) combines dense and sparse regions to optimize energy coverage, while the SWGO-A configuration (b) represents a more compact array focused on lower-energy performance. Panel (a) adapted from Valore and Collaboration [49], panel (b) adapted from [3].

The layout shown in Fig. 3.9 combines dense sampling of lower-energy showers with a larger effective area for high-energy events, while balancing reconstruction performance, construction cost, and deployment feasibility.

More generally, WCD-array design involves a trade-off between dense sampling at low energies and large effective area at high energies. A dense core improves the detection and reconstruction of lower-energy showers, while a larger outer array increases the effective area for high-energy events. SWGO layout studies therefore seek to balance energy coverage, reconstruction performance, gamma-hadron separation, construction cost, and deployment feasibility.

3.3.2 Double-Layer Water Cherenkov Detector Design

A key development in the SWGO detector concept is the use of double-layer water Cherenkov detector (WCD) units. In this design, the water volume is divided into two optically separated chambers, each instrumented with photomultiplier tubes. This vertical segmentation allows the detector to compare the response of an upper electromagnetic-shower volume with a lower volume more sensitive to penetrating particles, especially muons. The concept is therefore directly relevant for gamma-hadron separation.

One representative large double-layer geometry is the D-type detector unit considered in the SWGO M5 detector-unit and array-configuration study. It is shown schematically in Fig. 3.10. This configuration should be understood as a candidate geometry used in detector-optimization studies, rather than as a final fixed detector design. Its relevance here is that it illustrates how a double-layer WCD links shower-component separation to PMT-based light detection.

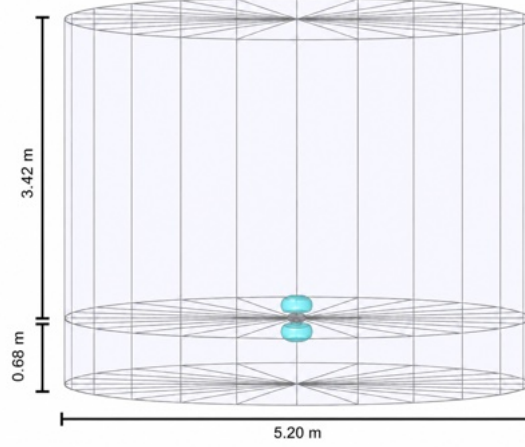


Figure 3.10: Large double-layer water Cherenkov detector unit corresponding to configuration D in the SWGO M5 detector-unit study. The configuration has a diameter of 5.20 m, an upper chamber depth of 3.42 m, and a lower chamber depth of 0.68 m. It uses a 10" high-quantum-efficiency PMT in the upper chamber and an 8" PMT in the lower chamber. The upper chamber is used mainly for electromagnetic-shower timing and charge measurement, while the lower chamber enhances penetrating-muon identification for gamma-hadron separation. Adapted from [16].

The operating principle is illustrated in Fig. 3.11. Electrons and positrons from the electromagnetic shower component produce Cherenkov light mainly in the upper chamber. Muons, which are more common in hadron-induced showers, can penetrate both layers and produce a correlated upper-lower signal. This chamber-wise comparison provides a detector-level observable for identifying muon-rich events [3, 29].

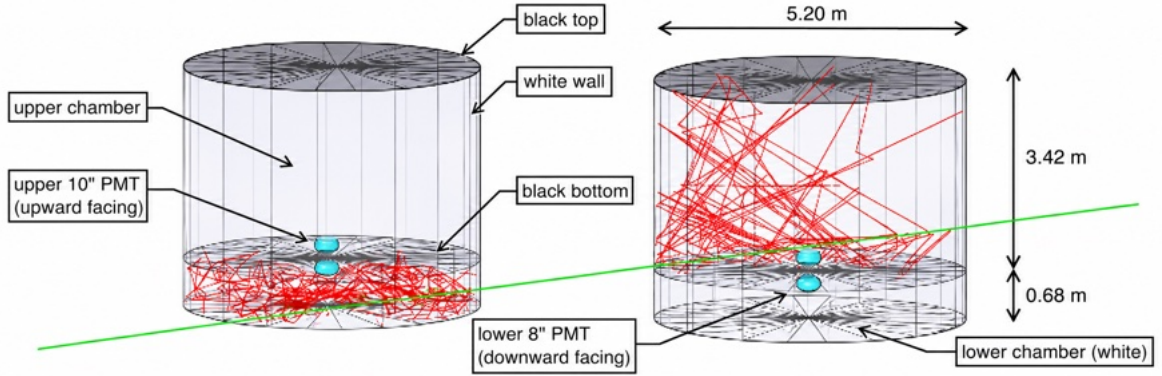


Figure 3.11: Schematic illustration of electromagnetic and muonic response in a large double-layer water Cherenkov detector unit based on the D-type SWGO M5 configuration. The upper chamber records Cherenkov light from the electromagnetic shower component, while the lower chamber provides sensitivity to penetrating muons. Red lines indicate representative Cherenkov photon paths, and the green trajectory represents a muon crossing both detector layers. Detector dimensions and PMT layout are based on [16]; the response principle follows the double-layer WCD concept discussed by [29].

The double-layer design therefore converts the physical difference between electromagnetic and muon-rich shower components into a measurable detector response. Gamma-ray-induced showers are expected to produce stronger relative activity in the upper chamber, whereas hadronic showers more often produce signals in both chambers because of their larger muon content. This improves gamma-hadron discrimination and adds information on the internal structure of the shower [29, 3].

In this detector concept, PMT quantum efficiency controls the conversion of Cherenkov photons into photoelectrons and therefore contributes directly to the available photoelectron statistics

in each detector unit. The wavelength-dependent QE response is consequently relevant to the charge and timing information obtained from the Cherenkov light recorded in the upper and lower chambers.

Chapter 4

Photomultiplier Tubes and Quantum Efficiency Fundamentals

4.1 Photomultiplier Tubes in the ANTARES Optical Module

In ANTARES, the photomultiplier tube was operated as the central photosensor of a complete optical module. The module protected the PMT from deep-sea pressure, provided optical coupling to the surrounding water, reduced the influence of the geomagnetic field, and integrated the high-voltage and signal connections into the detector readout system. This original detector environment is relevant to the present thesis because the investigated PMTs are recovered components from a long-term deep-sea Cherenkov detector rather than unused laboratory devices.

ANTARES detected Cherenkov light emitted by relativistic charged particles produced in neutrino interactions near the detector. The arrival times and intensities of the recorded photon signals were used to reconstruct the direction and properties of the resulting particle tracks. Since the detector operated at a depth of approximately 2500 m in the Mediterranean Sea, each PMT was enclosed within a transparent pressure-resistant glass sphere [12].

The optical module provided the mechanical protection and local operating environment of the PMT. The glass sphere formed the pressure housing, the optical gel coupled the PMT to the sphere, the magnetic shield reduced field-induced changes in the electron trajectories, and the base and penetrator provided the electrical interface.

The module housed a 10" hemispherical Hamamatsu R7081-20 PMT. The surrounding glass sphere had an outer diameter of approximately 43.2 cm, which constrained the dimensions of the photosensor. The R7081-20 has a bialkali photocathode deposited on a borosilicate-glass input window and a minimum photocathode diameter of approximately 220 mm. Its spectral response extends approximately from 300 nm to 650 nm, with the highest sensitivity in the blue wavelength region relevant for Cherenkov-light detection in water [12, 22].

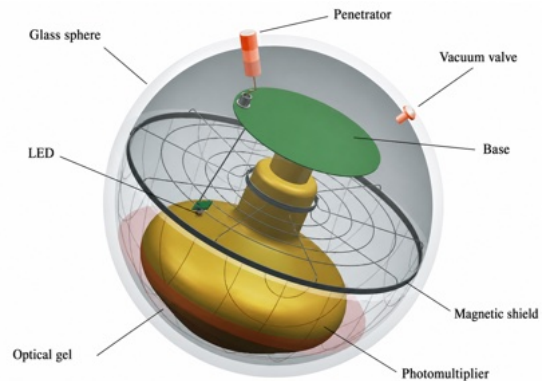


Figure 4.1: Schematic view of an ANTARES optical module, showing the pressure-resistant glass sphere, optical gel, magnetic shield, internal LED, PMT base, and photomultiplier tube. Adapted from [12].

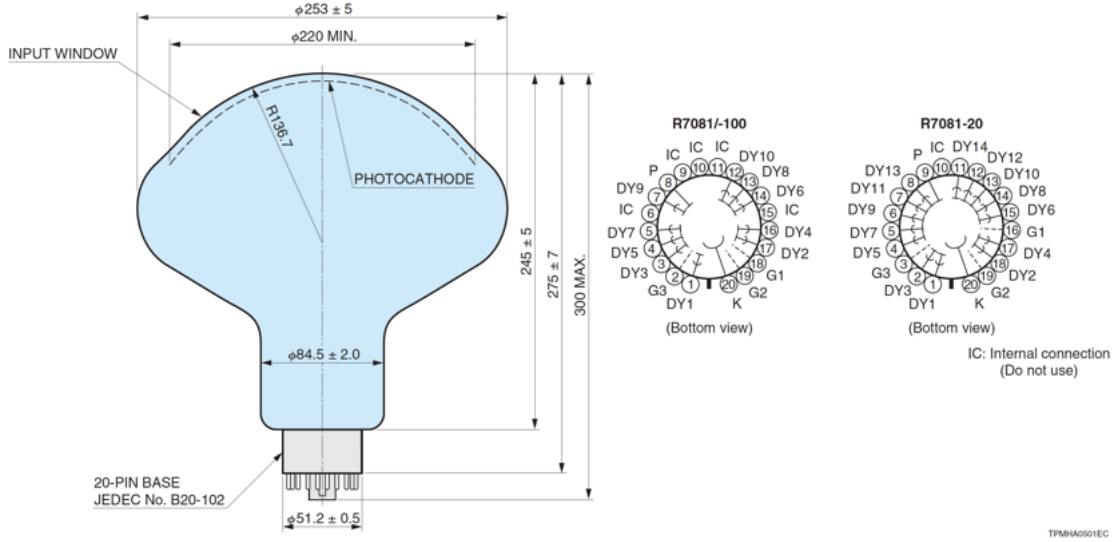


Figure 4.2: Dimensional outline and base layout of the Hamamatsu R7081-20 photomultiplier tube used in ANTARES. The tube has a 10" hemispherical input window, a minimum photocathode diameter of 220 mm, and a 20-pin base. Adapted from [22].

The R7081-20 was originally selected through a broad ANTARES qualification programme covering optical and operational performance. For the quantities relevant to this thesis, the ANTARES specification required a geometrical photocathode area greater than approximately 500 cm^2 , a quantum efficiency of at least 20 %, and a collection efficiency of at least 80 % over the photocathode surface [12].

Quantum efficiency describes the probability that an incident photon releases a photoelectron from the photocathode. Collection efficiency instead describes the probability that the released photoelectron is guided successfully towards the first dynode. This distinction is relevant when interpreting spatial measurements, because a position-dependent photocurrent can reflect variations in the photocathode conversion probability, the subsequent electron collection, or both.

The extracted PMTs investigated in this thesis have undergone long-term ANTARES operation, recovery, removal from the optical modules, extraction from the optical gel, cleaning, storage, and laboratory handling. The relevant question is therefore whether the recovered R7081-20 PMTs have retained their wavelength-dependent and spatial photocathode sensitivity after this history.

4.2 Operating Principle of a Photomultiplier Tube

A photomultiplier tube converts very weak optical signals into measurable electrical pulses. This is the reason PMTs are useful in Cherenkov detectors: a small number of incident photons can be transformed into a signal large enough to be processed by the readout electronics. In its basic form, a PMT consists of an input window, a photocathode, focusing electrodes, a dynode multiplication chain, and an anode. When light enters the tube through the input window, photons absorbed in the photocathode can release photoelectrons into the vacuum. These photoelectrons are guided towards the first dynode, multiplied through secondary emission at successive dynodes, and finally collected at the anode as an output pulse [38].

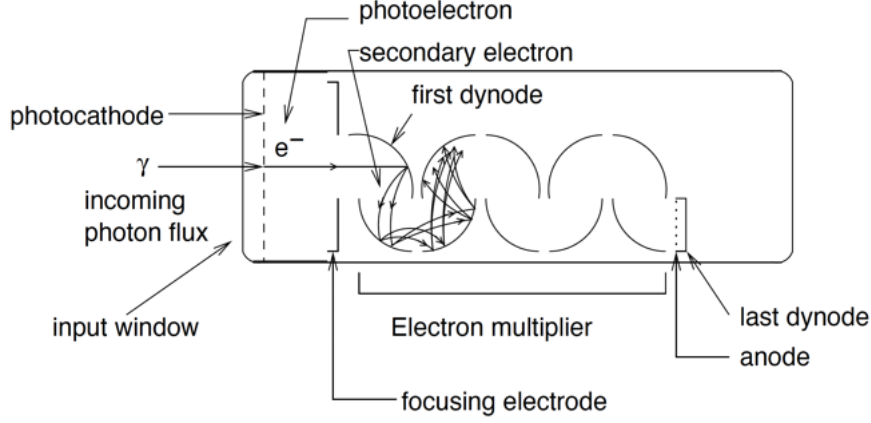


Figure 4.3: Schematic operating principle of a photomultiplier tube. Incident photons enter through the input window and release photoelectrons from the photocathode. The photoelectrons are focused towards the first dynode, where secondary emission starts an electron multiplication chain. The resulting electron avalanche is collected at the anode as an electrical pulse. Adapted from [38].

Photon Conversion at the Photocathode

The first stage of photomultiplier operation is photon conversion at the photocathode. The photocathode is a photosensitive semiconductor layer deposited on the inner surface of the input window. In a head-on hemispherical PMT such as the Hamamatsu R7081-20, this geometry provides a large sensitive area for incident light.

When an incident photon transfers sufficient energy to an electron in the photocathode material, the electron can overcome the surface barrier and escape into the vacuum of the tube. In the simplified photoelectric picture, the kinetic energy available to the emitted photoelectron is

$$E = h\nu - \phi, \quad (4.1)$$

where h is Planck's constant, ν is the photon frequency, and ϕ is the effective work function of the photocathode material. Therefore, only photons with energies above the effective emission threshold can produce photoelectrons.

Not every absorbed photon releases an electron into the vacuum. The wavelength-dependent probability of this conversion is quantified by the quantum efficiency, which is defined and discussed in detail in the following section [38].

Electron Collection and Multiplication

After emission, the photoelectron must be collected efficiently by the first dynode. This part of the PMT is called the electron-optical input system. Its task is to guide the emitted photoelectrons towards the multiplication region while keeping the collection probability as uniform as possible across the photocathode surface. For a large hemispherical PMT such as the Hamamatsu R7081-20, the focusing structure must collect photoelectrons produced over a wide photocathode area and direct them efficiently toward the first dynode.

The efficiency of this first transport step is described by the collection efficiency. In simplified form, it can be written as

$$\text{CE} = \frac{N_{\text{collected}}}{N_{\text{emitted}}}, \quad (4.2)$$

where N_{emitted} is the number of photoelectrons emitted from the photocathode and $N_{\text{collected}}$

is the number of those photoelectrons that reach the first dynode. If the focusing field is not sufficiently uniform, both the collection efficiency and the transit time can depend on the photon impact position [38].

Once the photoelectron reaches the first dynode, the multiplication process begins. Each dynode is held at a higher electric potential than the previous one, so electrons are accelerated from one stage to the next. When a primary electron strikes a dynode with sufficient energy, it releases several secondary electrons. Repeating this process over many dynode stages converts a single initial photoelectron into an electron avalanche large enough to produce a measurable anode pulse. For the Hamamatsu R7081-20 used in ANTARES, this multiplication system consists of 14 dynode stages in a box-and-line configuration [12, 22].

Signal Formation and Gain

The total gain of a PMT describes how many electrons are finally collected at the anode per initially emitted photoelectron. If the secondary emission factor of dynode k is δ_k , and the inter-dynode collection efficiency after that dynode is α_k , the gain can be written as

$$G = \prod_{k=1}^N \alpha_k \delta_k, \quad (4.3)$$

where N is the number of dynode stages. This expression shows that the measured output signal therefore depends not only on the photocathode quantum efficiency, but also on the collection efficiency of the electron-optical system and the multiplication efficiency of the dynode chain. Therefore, quantum efficiency, collection efficiency, and gain describe different parts of the PMT response and should not be treated as the same quantity [38].

The final electron avalanche is collected at the anode, producing a short current pulse. In single-photoelectron operation, the charge of this pulse corresponds to the multiplication of one initial photoelectron and can be written as

$$Q_{\text{SPE}} = eG, \quad (4.4)$$

where e is the elementary charge and G is the PMT gain. In practice, the charge distribution of many such pulses forms the single-photoelectron spectrum, which is commonly used to determine the gain and the peak-to-valley ratio. For detector operation, the pulse must be large enough to be separated from electronic noise, stable enough for calibration, and fast enough to preserve the timing information carried by the original Cherenkov photons. These were strict requirements for ANTARES because both photon-counting efficiency and timing precision directly affected event reconstruction in the sparse deep-sea detector geometry [12].

4.3 Quantum Efficiency as a Measure of Photon Sensitivity

Quantum efficiency describes the probability that an incident photon produces a photoelectron that escapes from the photocathode into the vacuum. It characterizes the photon-conversion process at the photocathode and is the central experimental observable used in this thesis to characterize the recovered PMTs [38, 22].

Quantum Efficiency

For a given wavelength λ , the quantum efficiency is defined as the ratio of the number of emitted photoelectrons to the number of incident photons:

$$QE(\lambda) = \frac{N_{pe}(\lambda)}{N_{\gamma}(\lambda)}, \quad (4.5)$$

where $N_{\gamma}(\lambda)$ is the number of photons incident on the photocathode and $N_{pe}(\lambda)$ is the number of photoelectrons emitted into the vacuum. Quantum efficiency is dimensionless and is commonly expressed as a percentage. The conversion process is illustrated schematically in Fig. 4.4.

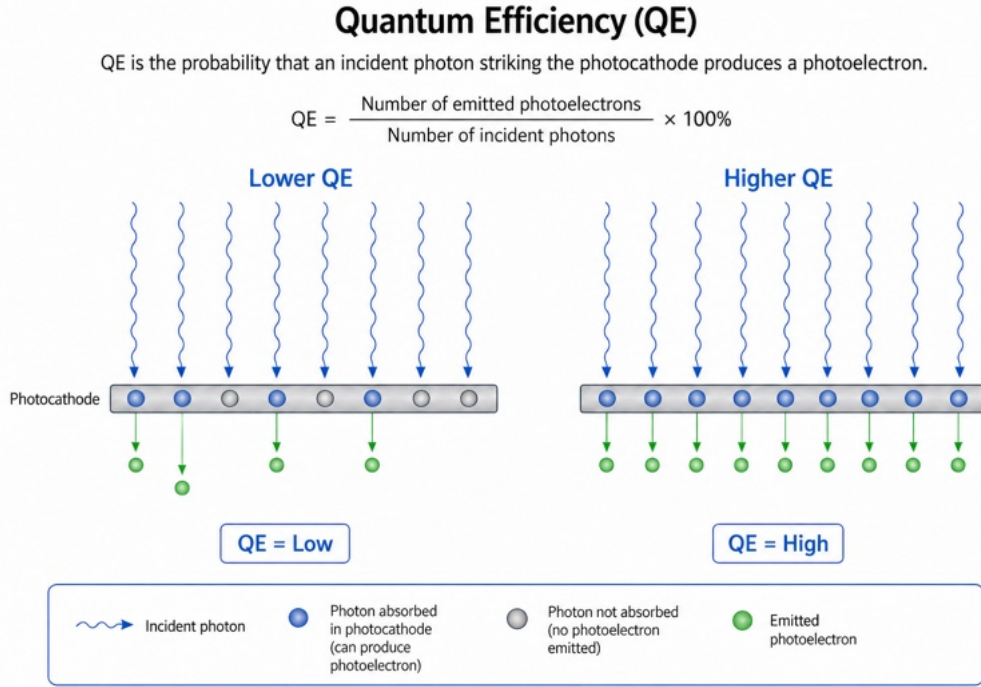


Figure 4.4: Schematic illustration of quantum efficiency at a photocathode. For the same number of incident photons, a lower quantum efficiency produces fewer emitted photoelectrons, while a higher quantum efficiency produces more emitted photoelectrons. The figure is a simplified author-made illustration.

An ideal photocathode in which every incident photon produces an emitted photoelectron would have a quantum efficiency of 100 %. Real photocathodes do not reach this limit because incident photons may be reflected, transmitted through the photocathode, or absorbed without releasing an electron into the vacuum. The resulting QE depends on the photon wavelength, the photocathode material and thickness, and the optical properties of the input window [38, 22]. Conventional bialkali photocathodes used in large-area PMTs typically reach their highest sensitivity in the near-ultraviolet and blue wavelength region.

The wavelength-dependent quantity $QE(\lambda)$ characterizes the present photocathode sensitivity of the extracted ANTARES PMTs after operation, recovery, cleaning, storage, and laboratory handling. It describes the conversion of incident photons into emitted photoelectrons and is distinct from the subsequent collection of those electrons by the dynode system.

4.3.1 Wavelength Dependence and Detection Efficiency

Quantum efficiency is not constant across the optical spectrum. Photon absorption and photoelectron emission depend on the photon energy and on the electronic and optical properties

of the photocathode material. For the bialkali photocathode of the Hamamatsu R7081-20, the sensitivity is highest in the near-ultraviolet and blue region and decreases towards both shorter and longer wavelengths [38, 22].

This wavelength dependence is particularly relevant in water Cherenkov detectors. Although Cherenkov emission is stronger at shorter wavelengths, the spectrum reaching a PMT is modified by absorption in water and transmission through the detector materials. The number of photoelectrons produced therefore depends on the overlap between the incident photon spectrum and the QE response of the photocathode. If the incident photon spectrum is described by $\Phi_\gamma(\lambda)$, the number of emitted photoelectrons is

$$N_{\text{pe}} = \int_{\lambda_1}^{\lambda_2} \Phi_\gamma(\lambda) \text{QE}(\lambda) d\lambda. \quad (4.6)$$

where $\Phi_\gamma(\lambda)$ is the number of photons incident on the photocathode per wavelength interval. The complete spectral response is therefore more informative than a single peak-QE value.

The approximate probability that an incident photon produces a photoelectron collected at the first dynode can be written as

$$\eta_{\text{det}}(\lambda) = \text{QE}(\lambda) \text{CE}, \quad (4.7)$$

or, when the spatial dependence is included,

$$\eta_{\text{det}}(\lambda, \mathbf{r}) = \text{QE}(\lambda, \mathbf{r}) \text{CE}(\mathbf{r}), \quad (4.8)$$

where $\mathbf{r}$ denotes the illumination position on the photocathode. This distinction is important for the spatial measurements presented later in the thesis, since a position-dependent photocurrent may contain contributions from both photocathode sensitivity and photoelectron collection.

Tube-specific wavelength-dependent QE measurements from before ANTARES deployment are not available for the complete extracted population. The post-recovery spectra are therefore evaluated using the TM0007 reference PMT, the ANTARES QE requirement, and comparisons within the measured population. These references allow the present spectral magnitude, shape, and spatial response of the recovered photocathodes to be characterized systematically.

4.4 Operational Performance Parameters and Relevance for SWGO Reuse

Quantum-efficiency measurements provide a direct assessment of whether the extracted ANTARES PMTs have retained their photocathode sensitivity and therefore supply an important basis for evaluating their potential reuse. The wavelength-dependent and spatial QE studies performed in this thesis characterize the present photon-conversion response of the recovered sensors. For additional assurance before detector deployment, this characterization should be complemented

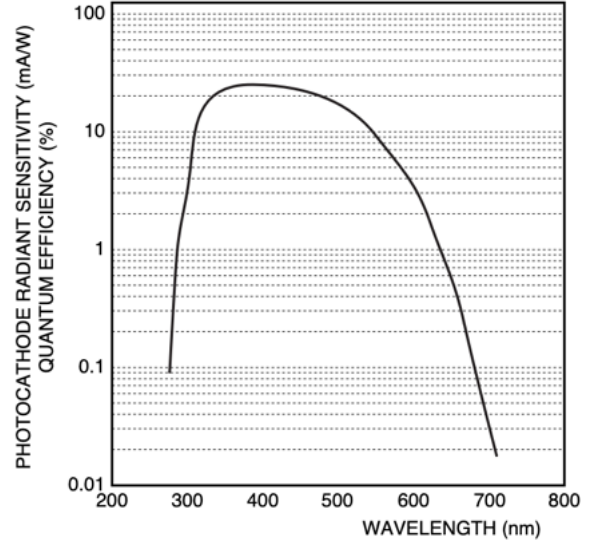


Figure 4.5: Typical spectral response of the Hamamatsu R7081-20 photomultiplier tube, showing photocathode radiant sensitivity and quantum efficiency as functions of wavelength. Adapted from Hamamatsu manufacturer data, as also used in ANTARES optical-module simulations [22, 28].

by measurements of gain, dark noise, timing response, pulse shape, afterpulsing, linearity, and long-term stability, which examine the subsequent stages of signal formation and the operational behaviour of the PMTs.

Gain, Noise, and Timing Stability

Gain describes the amplification between an emitted photoelectron and the charge collected at the anode. For a single-photoelectron pulse with charge Q_{SPE} , the gain is

$$G = \frac{Q_{\text{SPE}}}{e}, \quad (4.9)$$

where e is the elementary charge. A sufficient and stable gain is required to separate single-photoelectron signals from electronic noise and to maintain a reproducible charge calibration. The ANTARES R7081-20 PMTs were required to reach a gain of at least 5×10^7 [12]. A post-recovery gain measurement would therefore verify that the dynode multiplication system still operates reliably.

PMTs can also produce signals in the absence of incident light. When these signals are counted as individual pulses, the dark count rate is

$$R_{\text{dark}} = \frac{N_{\text{dark}}}{\Delta t}, \quad (4.10)$$

where N_{dark} is the number of dark pulses recorded during the interval Δt . Excessive dark noise increases the detector background and can reduce the reliability of photon-signal identification. A dark-noise measurement is therefore needed to determine whether the recovered PMTs remain suitable for low-light operation [12, 6].

The timing response describes how accurately the PMT preserves the arrival time of an incident photon. The transit time is defined as

$$t_{\text{T}} = t_{\text{anode}} - t_{\text{pe}}, \quad (4.11)$$

where t_{pe} is the photoelectron-emission time and t_{anode} is the time at which the corresponding anode pulse is recorded. Event-to-event variations are characterized by the transit time spread,

$$\text{TTS} = \text{FWHM}(t_{\text{T}}). \quad (4.12)$$

ANTARES required a transit time spread below 3 ns. Measuring the timing response after recovery would confirm whether the electron-optical and multiplication systems still provide the precision required for Cherenkov-event reconstruction [12].

Spurious Pulses and Long-Term Stability

Prepulses, late pulses, and afterpulses can generate additional signals that do not correspond directly to the arrival time of the incident photon. Their occurrence may be associated with electron backscattering, residual-gas ion feedback, or disturbances in the multiplication process. Measurements of these pulse populations are therefore needed to determine whether the recovered PMTs introduce delayed or incorrectly timed signals [38, 12].

Long-term stability measurements would additionally test whether gain, dark noise, timing response, and pulse shape remain reproducible during repeated operation. Such measurements provide further assurance that PMTs with acceptable wavelength-dependent and spatial QE also retain stable operational performance after recovery, cleaning, storage, and laboratory handling.

Contribution of Quantum Efficiency to the Reuse Assessment

Quantum efficiency directly characterizes the photon-conversion response of the photocathode. A reduction or distortion in $QE(\lambda)$ decreases the number of photoelectrons generated from the incident Cherenkov-light spectrum and therefore reduces the photon sensitivity of the detector unit.

For the extracted ANTARES PMTs, the wavelength-dependent and spatial QE measurements presented in this thesis characterize the present photocathode response after long-term detector operation, recovery, cleaning, storage, and laboratory handling. The measured spectra are evaluated through their magnitude, wavelength dependence, spatial behaviour, comparison with the TM0007 reference PMT, relation to the original ANTARES QE requirement, and comparison within the measured population.

PMTs showing a consistent spectral and spatial QE response can proceed to complementary operational qualification. PMTs with clearly reduced or anomalous QE responses can instead be identified before more extensive electrical, timing, and detector-integration studies are performed. The QE characterization therefore provides an experimentally defined basis for selecting and prioritizing recovered PMTs within the wider reuse programme.

Chapter 5

Experimental Setup and Measurement Methodology

5.1 Experimental Setup: Design, Construction, and Validation

Design

The setup was built to measure how extracted ANTARES photomultiplier tubes respond to monochromatic light as a function of wavelength and incidence angle. For each scan, the PMT photocurrent was measured and later compared with the current from a calibrated silicon photodiode exposed to the same optical beam. This comparison provides the basis for the quantum-efficiency calculation used in the following chapters.

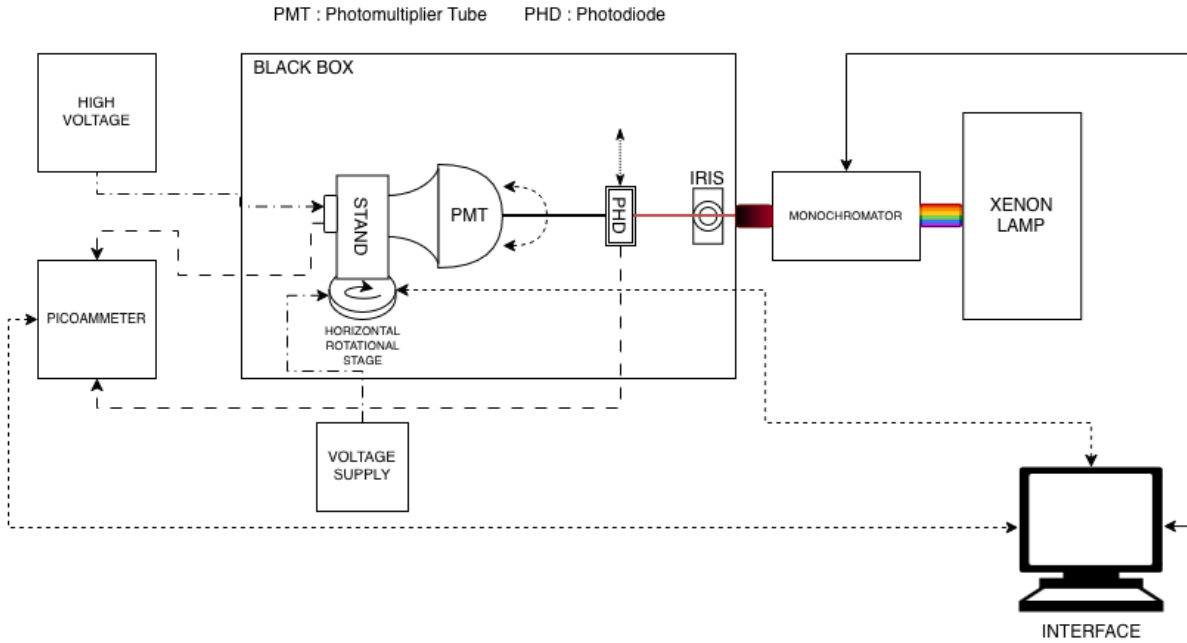


Figure 5.1: Schematic representation of the setup used for spectral and angular photocurrent measurements. The xenon lamp and monochromator provide wavelength-selected illumination, the iris defines the beam, and the light-tight box contains the calibrated photodiode and PMT measurement positions. The PMT is mounted on a horizontal rotation stage for angular scans, while the photocurrent is measured using a picoammeter.

A schematic overview of the setup is shown in Fig. 5.1. The optical chain begins with a xenon lamp, whose broadband emission is passed through a monochromator to select the required wavelength. The selected light is then restricted by an iris before entering the light-tight measurement box.

Inside the box, the beam path is arranged such that the same optical line can be used either for the calibrated photodiode measurement or for illuminating the PMT photocathode. For angular measurements, the PMT is mounted on a mechanical support attached to a horizontal rotation stage, allowing the angle of incidence to be varied while the external optical beam remains fixed. Three practical constraints determined the final layout. The light had to be wavelength-selective and reproducible, the measurement volume had to suppress ambient light, and the PMT had to rotate without changing the external beam alignment. For this reason, the setup used a fixed monochromator beam path, a light-tight black box, and a motorized rotation stage for angular scans.

The following subsections describe the equipment used in the setup, the construction of the measurement system, the light-tight validation, and the final measurement chain.

5.1.1 Construction

The measurement setup was constructed as a modular optical and electrical system. The optical chain was assembled around a xenon lamp, monochromator, iris aperture, and light-tight measurement box. The xenon lamp provided broadband illumination, the monochromator selected the wavelength, and the iris fixed the beam size before the light entered the box. Inside the box, the same beam line was used for the calibrated photodiode and for the PMT measurement. The PMT was mounted on a rotation stage to allow angular scans without changing the external optical alignment.

The modular layout also made alignment and troubleshooting easier, which was useful because the measured photocurrents were sensitive to light leaks, optical drift, and electrical noise.

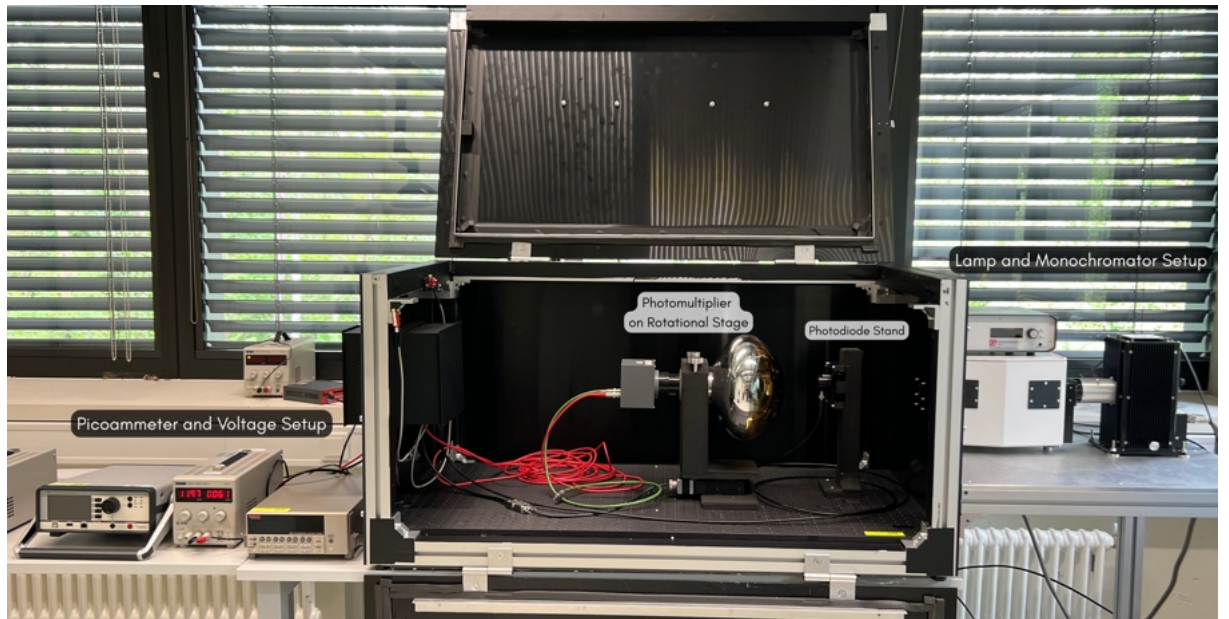


Figure 5.2: Photograph of the constructed experimental setup used for the spectral and angular photocurrent measurements. The light-tight black box forms the central measurement volume, with the PMT mounted inside on the rotation stage. The xenon lamp and monochromator are positioned on the right-hand side of the setup, while the picoammeter, high-voltage supply, and auxiliary electronics are placed externally for current readout and detector operation.

Light Source and Lamp Housing

The illumination system was built around a Quantum Design xenon arc lamp assembly. A 150 W ozone-free xenon lamp, model LSB523, was mounted inside the LSH102 lamp housing and operated using the LSN155 arc-lamp power supply. A xenon arc lamp was used because its broadband ultraviolet–visible emission covers the wavelength region where the bialkali photocathode is expected to respond most strongly. The lamp housing also provides convection cooling and external arc-position adjustment, which allowed the light source to be aligned without repeatedly disturbing the downstream optical elements [43, 44].

The lamp was therefore treated as a broadband input spectrum, from which the monochromator selected the wavelength interval used for each measurement.

Wavelength Selection with the Monochromator

The broadband xenon-lamp output was coupled into a Quantum Design MSH-300 monochromator, which selected the illumination wavelength for both the photodiode and PMT measurements. The MSH-300 is a 300 mm focal-length Czerny–Turner monochromator with software control of the grating position, filter wheel, and slit settings. This enabled automated wavelength scans under reproducible optical conditions [41, 42].

The optical layout is shown in Fig. 5.4. Light entering through the entrance slit is collimated by an internal mirror, diffracted by a plane grating, and then focused onto the exit slit. The grating position selects the output wavelength, while the entrance and exit slit widths control the spectral bandwidth and transmitted intensity. The filter wheel suppresses unwanted higher diffraction orders and can also block the light path during dark-current measurements.

The slit widths define the trade-off between optical throughput and wavelength resolution. A wider slit increases the transmitted intensity but broadens the wavelength interval reaching the detector, whereas a narrower slit improves spectral selectivity at the cost of lower signal. In this setup, the slit settings were chosen so that both PMT and photodiode currents remained measurable while preserving sufficient wavelength resolution [41, 42].

Order sorting was also necessary because a diffraction grating can transmit overlapping wavelength orders. Light at shorter wavelengths in higher diffraction orders can contribute to the selected



Figure 5.3: Xenon arc lamp housing used as the broadband illumination source.

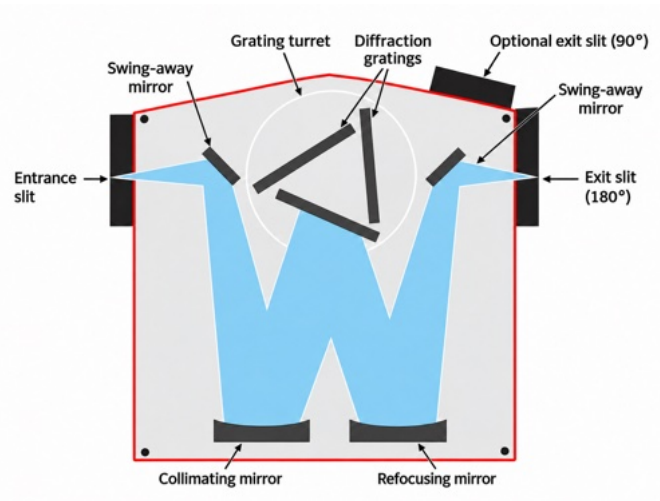


Figure 5.4: Simplified optical configuration of the MSH-300 monochromator. The entrance slit, internal mirrors, diffraction grating, exit slit, and filter wheel define the wavelength-selected output beam. Adapted from the Quantum Design MSH-300 documentation [41, 42].

first-order output if it is not filtered. The motorized filter wheel of the MSH-300 was therefore used to select appropriate order-sorting filters during spectral scans, while its blind position was used to block the light path for dark-current measurements [41, 42].

Beam Definition and Entry into the Black Box

After the monochromator, an iris aperture was placed in the beam path to define the beam geometry before the detector region. The iris did not select the wavelength; it restricted the beam diameter and reduced stray light. During the measurements, the iris was set to approximately 8 mm, keeping the beam smaller than the 10 mm $\times$ 10 mm active area of the calibrated photodiode. This ensured that the full beam was incident on the photodiode during reference measurements.

The same iris setting was kept for the PMT measurements so that the photodiode and PMT were exposed to the same optical beam geometry. Changes in measured current should therefore originate from the detector response and wavelength setting, not from changes in beam size or aperture alignment.

The black box formed the light-tight measurement volume. Its purpose was to suppress ambient light so that the measured detector current was dominated by the monochromator beam. Optical entry points and cable openings were therefore shielded to reduce light leakage and background-current contributions.

Reference Photodiode

Inside the black box, a calibrated silicon photodiode was used as the reference detector. The photodiode measurement was necessary because the PMT current alone does not provide the incident light intensity at each wavelength. The photodiode used in this setup was a Bentham DH-Si detector, serial number 38449/2, calibrated over the range 250 nm to 1100 nm in 5 nm steps [15]. Its active detector dimensions were 10 mm by 10 mm, corresponding to an active area of

$$A_{PD} = 10 \text{ mm} \times 10 \text{ mm} = 100 \text{ mm}^2. \quad (5.1)$$

During the measurements, the iris diameter was set to approximately 8 mm diameter, so that the beam remained within the active photodiode area. This reduced the risk of clipping at the detector boundary and ensured that the reference current represented the complete incident beam.

The calibrated photodiode provides the wavelength-dependent reference current required for the relative QE calculation. Its manufacturer-provided responsivity was converted once into photodiode QE. The implemented analysis then used the dark-corrected PMT and photodiode currents directly, together with the calibrated photodiode QE, to determine the PMT quantum efficiency.

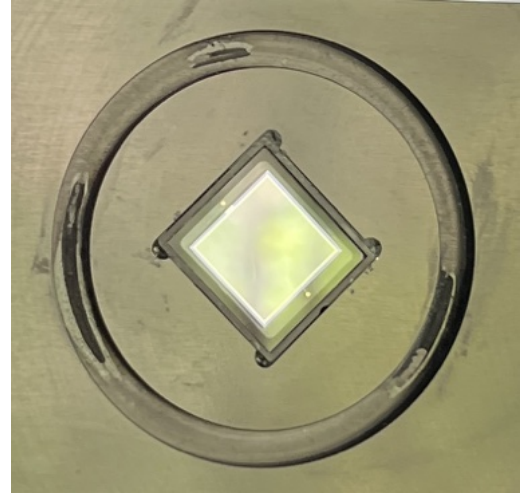


Figure 5.5: Bentham DH-Si Detector 38449/2: Photodiode.

Photomultiplier Tube Mounting and Rotation Stage

For the PMT measurements, the extracted ANTARES PMT was mounted on a mechanical support fixed to a Thorlabs HDR50/M motorized rotation stage. The HDR50/M stage provides continuous 360° rotation and is designed for heavy-duty use, with a specified on-axis load capacity of 50 kg. Its worm-drive mechanism and microstepping control make it suitable for repeatable angular positioning of the PMT during angular scans [48].

The rotation stage allowed different regions of the photocathode to be illuminated without changing the external optical path. The monochromator beam and iris remained fixed, while the PMT was rotated about the vertical stage axis. The PMT position on the stage was chosen so that, at the reference stage position, the beam intersected the central region of the photocathode and was aligned with the local surface normal. The beam was therefore incident at 90° to the local photocathode surface, corresponding to normal incidence.

The distance between the rotation axis and the illuminated photocathode region was fixed by the mounting geometry. This rotation radius was selected so that rotating the stage moved the beam across the curved photocathode while keeping the external beam path unchanged. Positive and negative stage rotations consequently illuminated opposite sides of the photocathode relative to the central position.

The angular coordinate used in the analysis is defined as

$$\theta = \theta_{\text{stage}} - \theta_0, \quad (5.2)$$

where θ_{stage} is the measured rotation-stage position and θ_0 is the stage position at which the fixed beam illuminates the photocathode centre at normal incidence. With this convention, $\theta = 0^\circ$ denotes the central normal-incidence configuration. Increasing $|\theta|$ moves the illuminated region away from the photocathode centre and towards the edge.

Photomultiplier Electrical Configuration

The Hamamatsu R7081-20 was operated in photocathode-current mode using a dedicated resistor-free base. The photocathode was connected directly to the Keithley 6487 picoammeter and remained close to 0 V. All dynodes, from D_1 to D_{14} , and the anode were electrically connected to one common node held at +450 V.

The electrode connections were arranged as follows:

Photocathode K : connected to the picoammeter input and maintained near ground potential;

Dynodes D_1 – D_{14} : electrically connected together without resistors between successive stages;

Anode P : connected to the same common node as the dynodes;

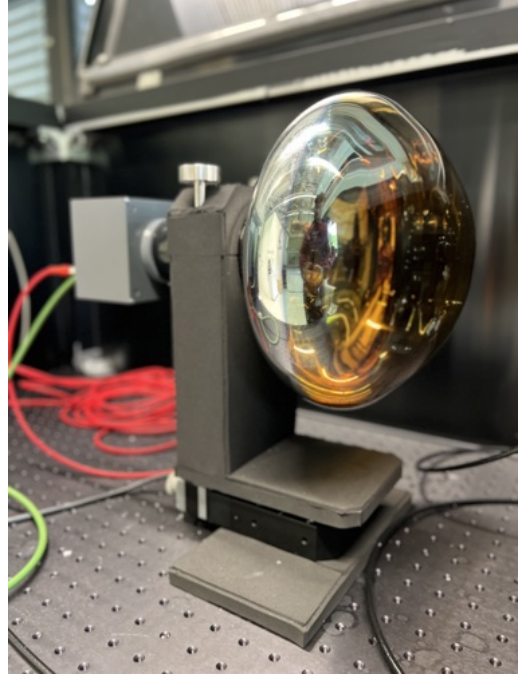


Figure 5.6: PMT mounted on the motorized horizontal rotation stage inside the black box.

Common collection node: held at +450 V relative to the photocathode.

Since no voltage-divider chain was present, there were no successive potential differences between the dynodes. The PMT therefore operated without dynode multiplication. The applied electric field extracted photoelectrons from the photocathode and collected them at the common positive electrode node.

The picoammeter measured the photocathode current rather than a first-dynode current or a multiplied anode current. No PMT gain or electronic amplification factor was therefore included in the quantum-efficiency calculation.

Figure 5.7 shows the electrical configuration used during the measurements.

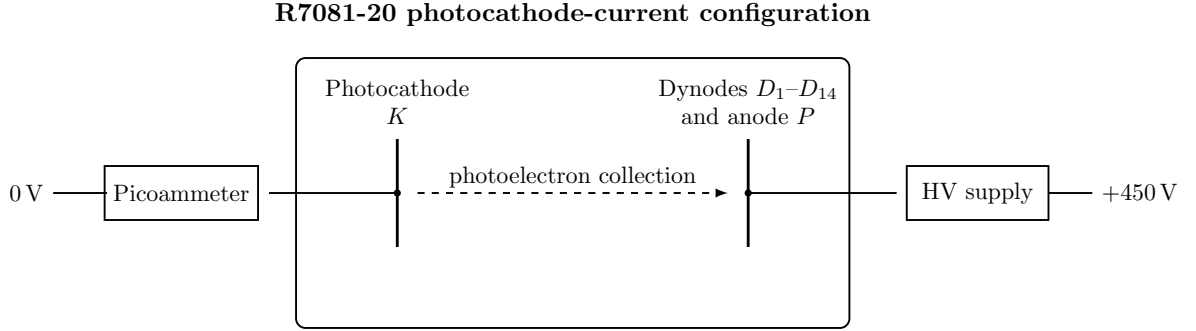


Figure 5.7: Simplified electrical configuration used for the photocathode-current measurement. The photocathode was connected to the Keithley 6487 picoammeter and remained near ground potential. All dynodes and the anode were connected to a common +450 V node without a voltage-divider chain.

Current Readout and Biasing

The photocurrent from either the photodiode or the PMT was measured using a Keithley 6487 picoammeter. The picoammeter was used because both detectors operate in a low-current regime under the selected illumination conditions. The PMT was operated using an external high-voltage supply, while the current signal was read out separately through the picoammeter.

The measured current can be written in simplified form as

$$I_{\text{meas}}(\lambda) = I_{\text{photo}}(\lambda) + I_{\text{dark}}(\lambda) + I_{\text{offset}}, \quad (5.3)$$

where I_{photo} is the light-induced photocurrent, I_{dark} is the detector dark current, and I_{offset} represents instrumental offsets or residual background contributions. The useful signal for the quantum-efficiency measurement is therefore the dark-corrected photocurrent,

$$I_{\text{corr}}(\lambda) = I_{\text{meas}}(\lambda) - I_{\text{dark}}(\lambda). \quad (5.4)$$

This decomposition shows that measurement quality depends not only on the lamp and monochromator, but also on the black-box sealing, cable routing, grounding, and stability of the readout electronics.

Final Measurement Chain

After construction, the complete setup followed the fixed measurement chain

$$\text{Xe lamp} \rightarrow \text{Monochromator} \rightarrow \text{Iris} \rightarrow \text{Black Box} \rightarrow \text{Photodiode/PMT} \rightarrow \text{Picoammeter}. \quad (5.5)$$

This arrangement provided two measurement modes. In the reference mode, the calibrated photodiode recorded the wavelength-dependent reference photocurrent. In the PMT mode, the

PMT photocurrent was recorded under the same wavelength-selected illumination. The rotation stage then extended this setup from a purely spectral measurement to an angular-response measurement.

5.1.2 Light-Tight Validation

The PMT and photodiode measurements were performed inside a light-tight black box. This enclosure was required because the measured photocurrents were small, particularly during dark-current and low-intensity measurements. Ambient light entering the box would contribute directly to the measured current and introduce a systematic offset in the subsequent quantum-efficiency calculation.

During the measurements, the laboratory windows were kept closed and the blinds were fully drawn in order to reduce variations in the ambient light level. The black-box enclosure therefore provided the main optical isolation of the detectors from the remaining laboratory illumination.

Potential leakage points included the front door of the enclosure, side panels, cable feedthroughs, the optical entrance, and the mechanical joints around removable parts of the enclosure. These regions were covered or sealed using black shielding material, overlapping closure surfaces, and neoprene tape. The sealing procedure was intended to suppress the detector response to external room light so that the measured current was determined primarily by the monochromator illumination and the detector baseline.

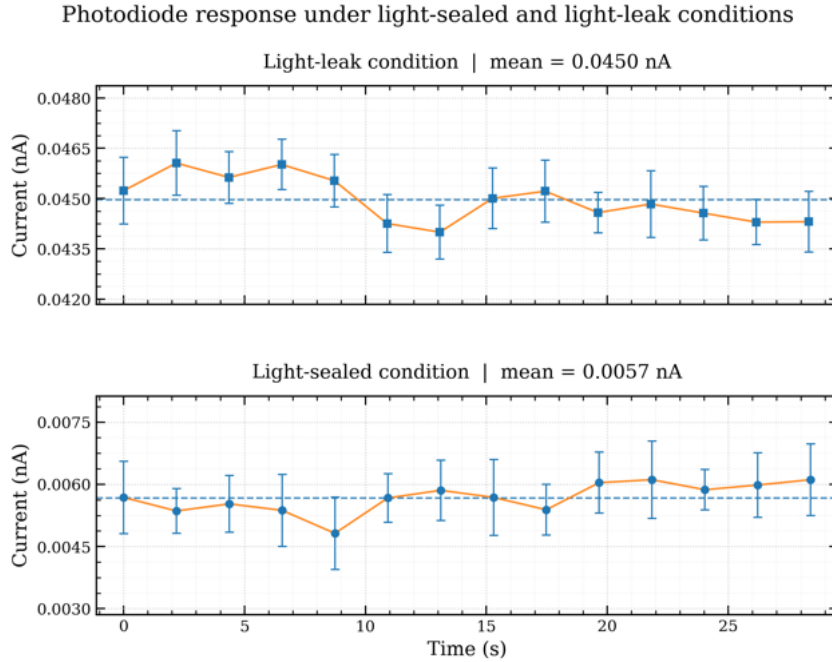


Figure 5.8: Photodiode response measured under an intentionally introduced light-leak reference condition and under the final sealed condition. For the reference measurement, the door of the black-box enclosure was deliberately left open, allowing ambient laboratory light to reach the detector. After the enclosure was closed and the possible leakage points were sealed with neoprene tape, the mean measured current decreased from approximately 0.0450 nA to approximately 0.0057 nA.

The enclosure was tested using the calibrated photodiode. The photodiode was placed inside the black box and its current was recorded under two configurations. For the reference measurement shown in Fig. 5.8, the door of the black box was deliberately left open, providing a reproducible light-leak condition in which ambient laboratory light could enter the enclosure. The door was then closed and the suspected leakage points were sealed before the measurement was repeated under the final configuration.

As shown in Fig. 5.8, the mean photodiode current decreased from approximately 0.0450 nA under the intentionally introduced light-leak condition to approximately 0.0057 nA after sealing. The corresponding ratio is

$$R_{\text{reference/sealed}} = \frac{\bar{I}_{\text{reference}}}{\bar{I}_{\text{sealed}}} = \frac{0.0450 \text{ nA}}{0.0057 \text{ nA}} \approx 7.9. \quad (5.6)$$

The sealing procedure therefore reduced the measured response to ambient laboratory light by a factor of approximately 7.9 relative to the deliberately introduced open-door reference condition. The remaining current of approximately 0.0057 nA represents the measured baseline under the tested sealed configuration and should not be interpreted as an absolute upper limit on residual optical leakage. This remaining baseline was accounted for through the dark-current measurements performed as part of each spectral and angular scan.

5.2 Instrument Control and Data Acquisition

The measurements were controlled with Python scripts developed for the different scan modes used in this work. The scripts set the monochromator wavelength and slit width, read the Keithley picoammeter, recorded dark-current blocks, controlled the rotation stage for angular scans, and saved the data with the relevant metadata.

Two main acquisition scripts were used. The first script was used for spectral scans at fixed detector position, including pre- and post-dark-current measurements and multi-segment wavelength scans with constant slit-width control. The second script extended this procedure to angular measurements by adding motorized rotation-stage control, allowing a complete wavelength scan to be repeated at each selected PMT angle.

5.2.1 Automation Rationale and Measurement Workflow

Automation was necessary because the same scan structure had to be repeated for many PMTs and, in the angular measurements, for many PMT orientations. Manual operation would have made the scans slower and less reproducible. The automated workflow kept the wavelength stepping, dark-current acquisition, current readout, and data storage consistent between scans.

A simplified overview of the measurement workflow is shown in Fig. 5.9.

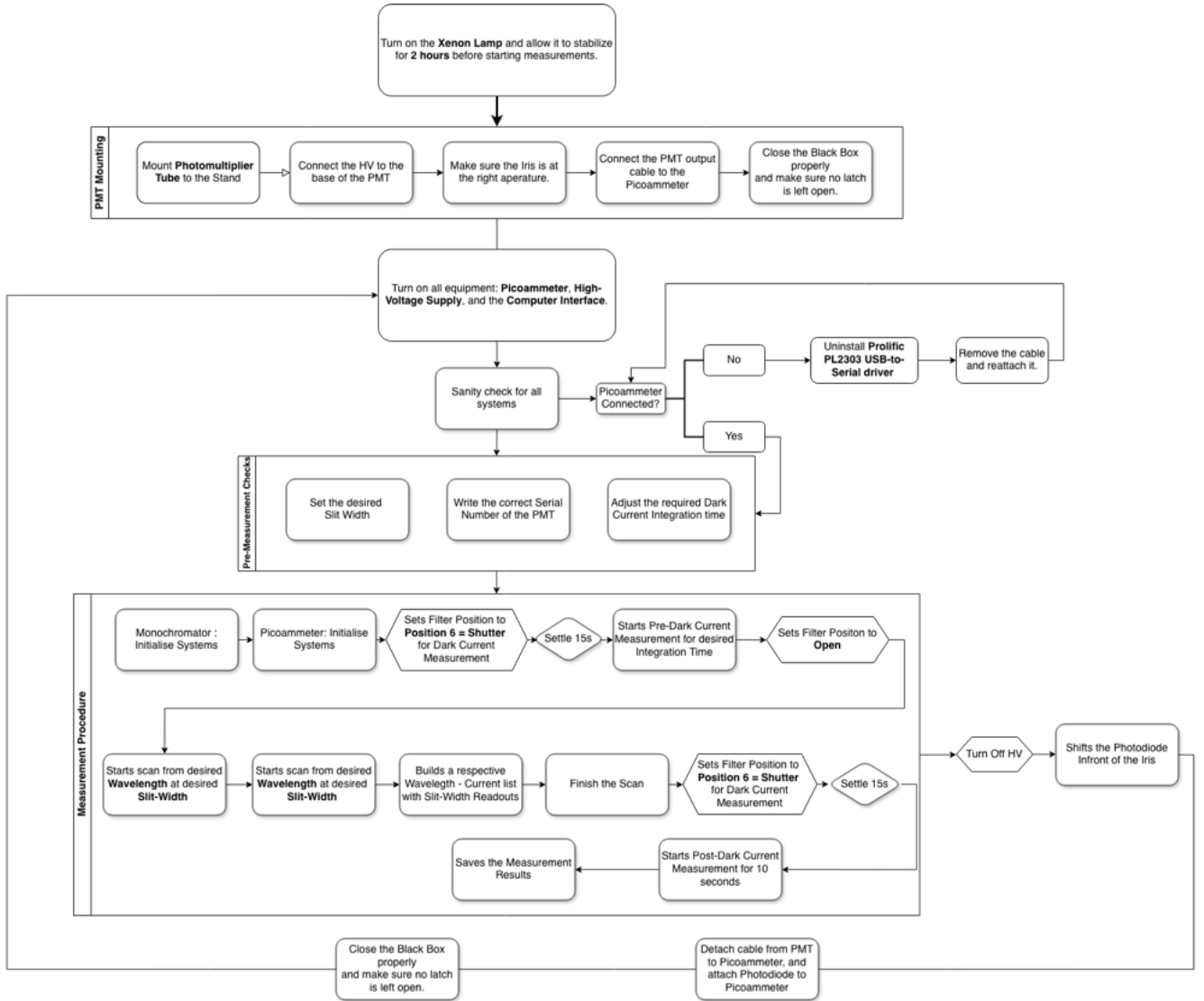


Figure 5.9: Simplified workflow of the automated measurement procedure used for the PMT and photodiode scans.

Before each scan, the xenon lamp was allowed to stabilize and the detector, high-voltage supply, picoammeter, monochromator, and computer-control interfaces were checked. After initialization, the software configured the wavelength range, slit-width settings, integration parameters, and dark-current acquisition sequence. The scan was then executed automatically and the measured data were stored in timestamped CSV files.

Software Environment and Instrument Interfaces

The acquisition software was written in Python and provided a common interface to the main measurement instruments. The Keithley 6487 picoammeter was controlled using PyVISA, while the Quantum Design MSH-300 monochromator was controlled by calling functions from the manufacturer-provided LOT dynamic-link library (DLL) using Python’s built-in `ctypes` module. For angular scans, the motorized rotation stage was additionally controlled through the TMCL interface using the `pytrinamic` package.

These interfaces combined wavelength and slit/filter control, current readout, dark-current acquisition, and angular positioning within the automated measurement scripts. The validation of the monochromator wavelength readback is described in Sec. 5.3.1.

5.3 Calibration, Stability, and Systematic Effects

5.3.1 Integrated Measurement-Control and Wavelength Readback

The automated measurement procedure was built around three coordinated control blocks. The monochromator block handled wavelength selection, wavelength readback, slit-width adjustment through bandwidth control, and filter-wheel positioning. The picoammeter block configured the Keithley 6487 and acquired current measurements over defined time windows. For angular scans, the rotation-stage block positioned the PMT at the requested angle and read back the actual stage position.

During each wavelength step, the commanded wavelength was compared with the monochromator readback. The reported wavelength was stored together with the current measurement and used to verify that the automated scan followed the intended wavelength sequence. Since wavelength selection in the MSH-300 depends on the motorized grating position, as described in Sec. 5.1.1, this comparison also provided a direct check of the monochromator positioning.

The acceptance condition was

$$|\lambda_{\text{act}} - \lambda_{\text{req}}| \leq \Delta\lambda_{\text{tol}}, \quad (5.7)$$

where λ_{req} is the requested wavelength, λ_{act} is the wavelength read back from the monochromator, and $\Delta\lambda_{\text{tol}}$ is the allowed tolerance. In the measurement scripts, this tolerance was typically set to 0.05 nm. If the monochromator did not reach the requested wavelength within the timeout, the actual wavelength was retained for later analysis. This ensured that the analysis used the measured instrument state rather than only the nominal command value.

5.3.2 Monochromator Communication, Optical Configuration, and Transition Systematics

The monochromator defined the wavelength, spectral bandwidth, and optical throughput of the beam incident on the photodiode or PMT. The MSH-300 is a Czerny–Turner monochromator in which wavelength selection is performed by rotating a diffraction grating, while the entrance and exit slits define the spectral bandwidth and transmitted intensity. In the present setup, a motorized filter wheel was also used for order sorting and as a shutter during dark-current measurements.

The following subsections describe the monochromator settings and transitions that were relevant to measurement stability and systematic effects.

Optical Configuration, Slit Width, and Filter Wheel

The MSH-300 uses a motorized grating turret. In the configuration used for this work, the relevant gratings near the UV/visible transition were Grating 1 with 2400 grooves/mm and blaze wavelength 250 nm, and Grating 2 with 1800 grooves/mm and blaze wavelength 500 nm. The automatic monochromator configuration switched from Grating 1 to Grating 2 at approximately 400 nm. Since the two gratings have different wavelength-dependent efficiencies, this transition can introduce a throughput change near the switching region.

The entrance and exit slit widths determine both the transmitted light intensity and the spectral bandwidth. Wider slits increase optical throughput but broaden the wavelength interval reaching the detector, while narrower slits improve spectral definition but reduce the signal. For the QE measurements, the slit width therefore had to be chosen as a compromise: the photocurrent had to remain clearly measurable, but the PMT should not be exposed to unnecessarily high photon flux. The QE calculation assumes that the measured photocathode current is proportional to the incident photon flux,

$$I_{\text{PMT}} \propto \Phi_{\gamma}, \quad (5.8)$$

within the selected operating range. The main concern at high illumination is saturation of the photocathode response, for which the emitted current no longer increases proportionally with the incident photon flux.

The relevant quantity is the photocathode current density,

$$J_{\text{PMT}} = \frac{I_{\text{PMT}}}{A_{\text{illum}}}, \quad (5.9)$$

where A_{illum} is the illuminated photocathode area. A current density of approximately 10 nA cm^{-2} was treated as the region in which photocathode saturation could become relevant. The monochromator settings were therefore chosen to limit the incident optical flux and keep the measurement within the linear-response regime.

During setup optimization, the total measured photocathode current was kept below approximately (12 nA) to avoid possible PMT saturation or non-linear response. This value was used as an empirical operating limit for the fixed illumination geometry and should not be interpreted as a universal saturation threshold, since the corresponding current density also depends on the illuminated area. Measurements at reduced photon flux confirmed that the reconstructed QE remained unchanged within the measurement uncertainty.

The local slit response was treated as approximately linear,

$$k = \frac{dw}{dB}, \quad (5.10)$$

where w is the physical slit width, B is the monochromator bandwidth setting, and k is the local slit-width response coefficient, describing the change in physical slit width per unit change in the bandwidth setting. Since w is expressed in millimetres and B in nanometres, k has units of mm nm^{-1} .

The final spectral measurements used two slit-width regions:

$$w_{\text{target}} = \begin{cases} 0.310 \text{ mm}, & 280 \text{ nm} \leq \lambda \leq 395 \text{ nm}, \\ 0.120 \text{ mm}, & 400 \text{ nm} \leq \lambda \leq 700 \text{ nm}. \end{cases} \quad (5.11)$$

The wider UV-region slit increased the short-wavelength photocurrent, where the optical throughput was lower. The narrower visible-region slit reduced the transmitted flux after the 400 nm grating/filter transition, where the monochromator output increased. This kept both the photodiode and PMT currents within a suitable dynamic range and reduced the risk of nonlinear PMT response. The detailed effect of the slit-width change on the measured photocurrent near the transition is discussed in Sec. 6.2.2.

The filter wheel was used both for order sorting and for dark-current acquisition. Since a diffraction grating can transmit overlapping wavelength orders, order-sorting filters were required to suppress shorter-wavelength contamination. In the present configuration, Filter 2 was used from approximately 280 nm, Filter 3 from approximately 400 nm, and Filter 4 from approximately 700 nm. Filter position 6 contained a blank disk and was used as a shutter for dark-current measurements. The automatic Filter 2 to Filter 3 change near 400 nm was necessary for spectral purity, but it also changed the optical throughput and was therefore treated as a transition-region systematic.

Initial Photodiode Observation of the 400 nm Transition

Before the final QE measurement procedure was fixed, initial photodiode scans were performed to characterize the optical response of the lamp–monochromator system. Since the calibrated photodiode current is directly proportional to the optical power reaching the detector, these scans were used to identify instrumental features before introducing the PMT response.

The first detailed scan was performed from 280 nm to 700 nm with a wavelength step of 0.2 nm and a constant bandwidth setting of 0.07 nm. This scan is shown in Fig. 5.10. A clear discontinuity is visible at approximately 400 nm, coinciding with the automatic change from Grating 1 / Filter 2 to Grating 2 / Filter 3.

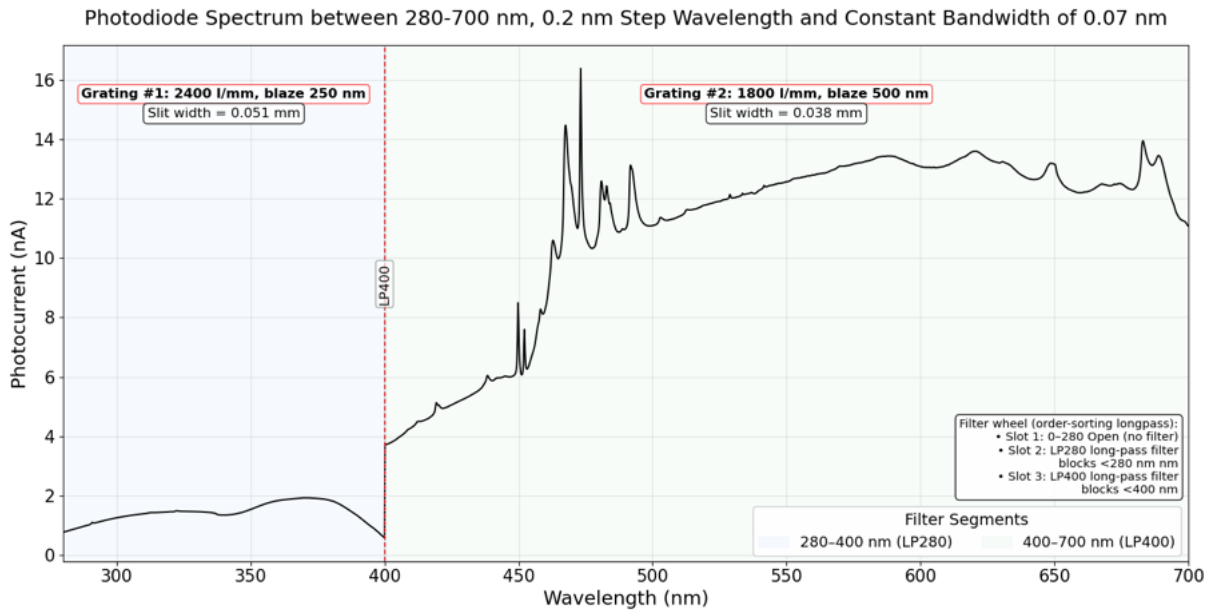


Figure 5.10: Detailed Photodiode spectrum measured from 280 nm to 700 nm with 0.2 nm wavelength steps and constant bandwidth of 0.07 nm.

Further scans were then performed using different fixed slit widths to check whether the discontinuity was related only to a specific intensity setting. Figure 5.11 shows spectra measured with slit widths of 0.04 mm, 0.06 mm, and 0.08 mm. As expected, increasing the slit width increased the transmitted optical flux. However, the discontinuity near 400 nm remained visible in all three spectra, confirming that it was associated with the monochromator configuration transition

rather than with a single accidental slit setting.

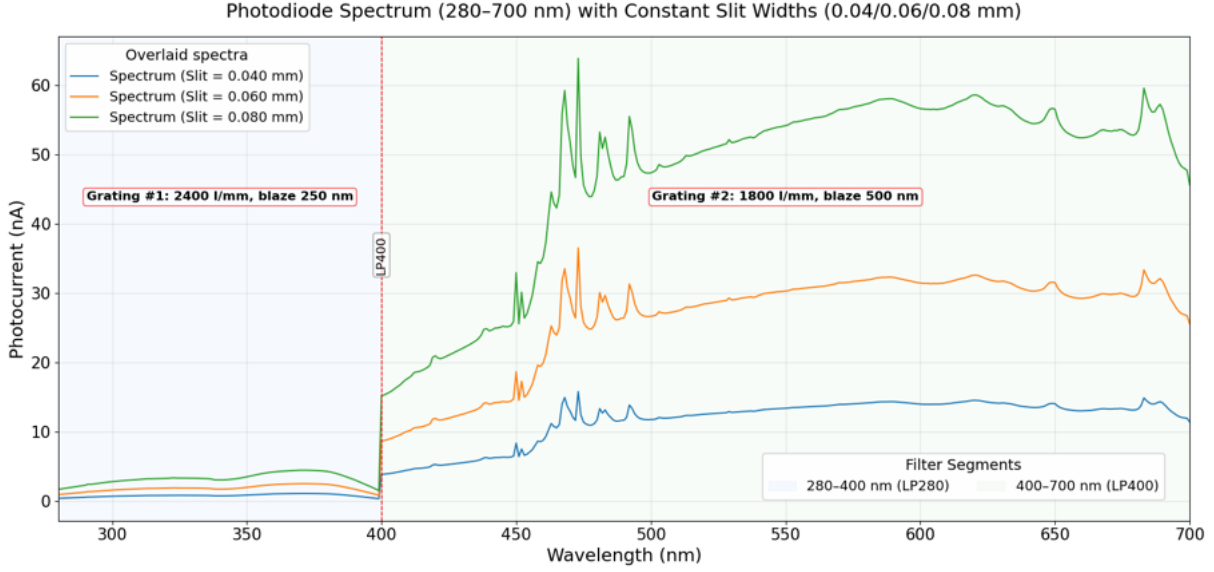


Figure 5.11: Photodiode spectra measured with constant slit widths of 0.04 mm, 0.06 mm, and 0.08 mm.

The discontinuity was therefore not interpreted as a property of the photodiode. The measured photodiode current can be written as

$$I_{PD}(\lambda) = R_{PD}(\lambda) P_{out}(\lambda), \quad (5.12)$$

where $R_{PD}(\lambda)$ is the calibrated photodiode responsivity and $P_{out}(\lambda)$ is the optical power leaving the monochromator. Since the photodiode responsivity varies smoothly over this narrow wavelength interval, an abrupt current jump around 400 nm must mainly originate from a change in $P_{out}(\lambda)$. These initial measurements motivated the controlled transition study described next.

5.3.3 Instrumental Systematic near the UV–Visible Transition

A dedicated study was performed around 400 nm using the calibrated photodiode to determine the origin of the discontinuity in the monochromator output. Four configurations were compared: the normal automatic grating and filter transition, a grating transition with the filter held fixed, a filter transition with the grating held fixed, and a scan in which both components remained fixed at Grating 1 / Filter 2.

The automatic configuration produced a pronounced current step at 400 nm, as shown in Fig. 5.12. A smaller step remained when only the grating was changed, whereas changing only the filter produced a larger discontinuity. No upward step was observed when both components were held fixed. The discontinuity is therefore associated with the change in the monochromator optical configuration rather than with the wavelength dependence of the photodiode itself. Among the two isolated changes, the filter-wheel transition produced the larger effect.

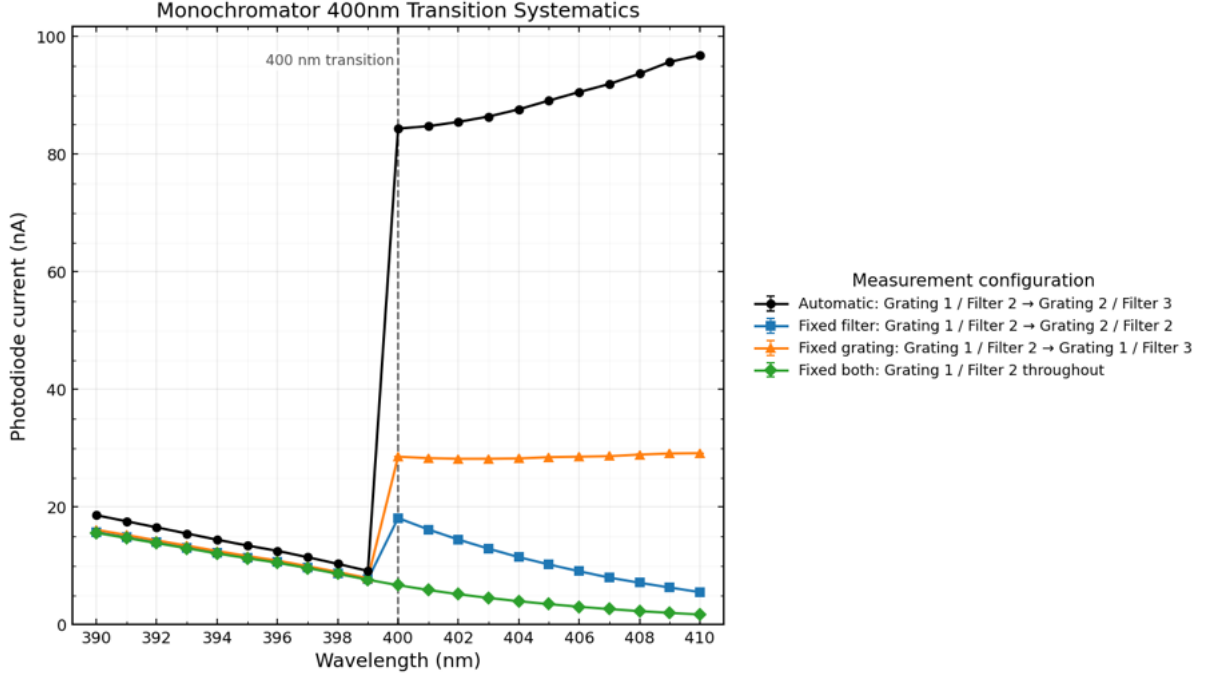


Figure 5.12: Photodiode current measured from 390 nm to 410 nm for the four monochromator configurations. Between 399 nm and 400 nm, the automatic configuration increased from approximately 9 nA to 84 nA. Changing only the grating increased the current from approximately 8 nA to 18 nA, while changing only the filter increased it from approximately 8 nA to 29 nA. The fixed-both scan remained continuous through the transition region.

The measured behaviour can be described through the wavelength-dependent monochromator throughput,

$$P_{\text{out}}(\lambda) = P_{\text{lamp}}(\lambda) \eta_g(\lambda) T_f(\lambda) T_s(\lambda), \quad (5.13)$$

where $P_{\text{lamp}}(\lambda)$ is the lamp output, $\eta_g(\lambda)$ is the grating efficiency, $T_f(\lambda)$ is the filter transmission, and $T_s(\lambda)$ represents the slit throughput. During the automatic transition, both the grating efficiency and the filter transmission change. The optical throughput on the two sides of 400 nm is therefore not continuous, even though the selected wavelength remains correctly defined.

Isolation of Grating and Filter-Wheel Contributions at Transition

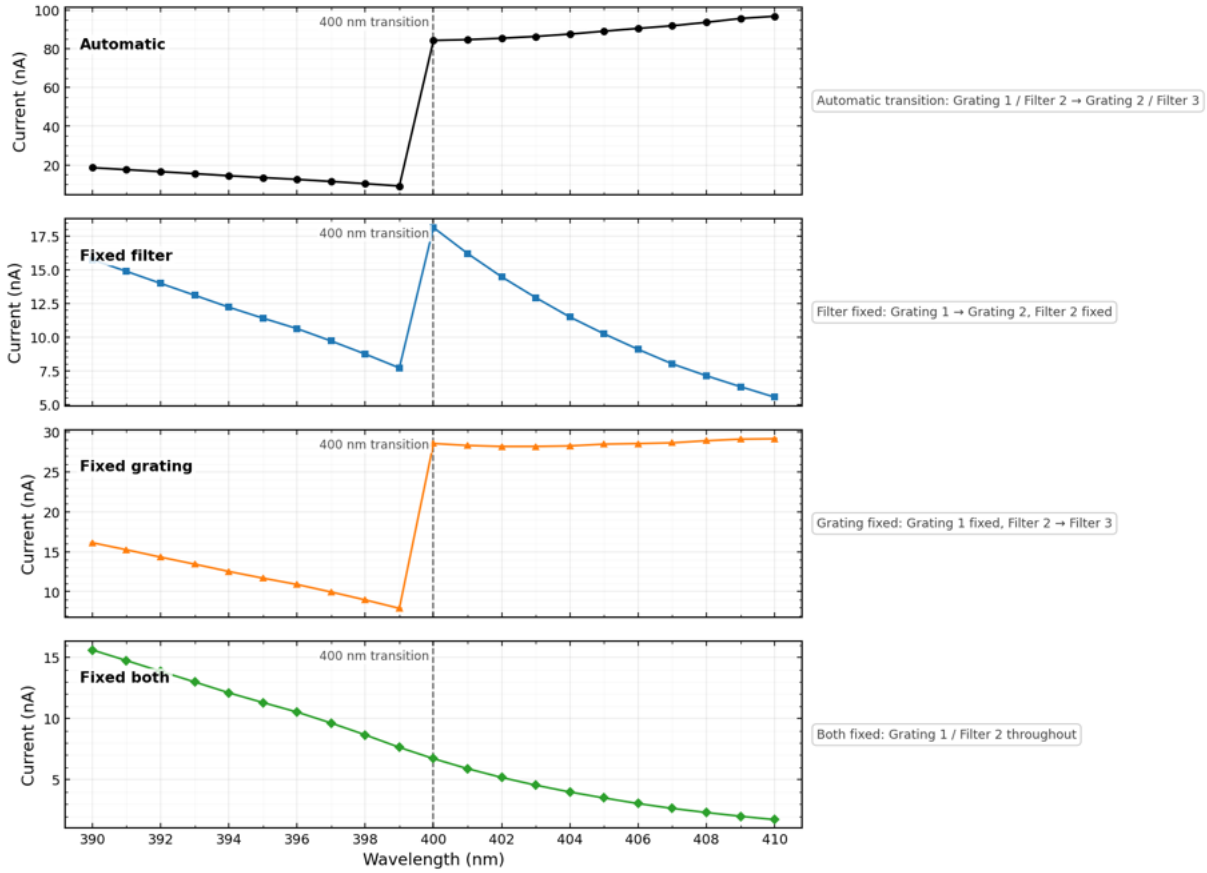


Figure 5.13: Separate comparison of the monochromator changes at 400 nm. Across the 399 nm to 400 nm interval, the isolated grating transition produced a current increase of approximately 10 nA, while the isolated filter transition produced an increase of approximately 21 nA. With both components fixed, the current followed the smooth decreasing trend observed below the transition.

Quantitatively, the automatic transition increased the photodiode current by approximately 75 nA, corresponding to a factor of about 9.4, or an increase of approximately 840 %. When only the grating was changed, the increase was approximately 10 nA, corresponding to a factor of about 2.3. When only the filter was changed, the increase was approximately 21 nA, corresponding to a factor of about 3.6. The simultaneous automatic change produced a substantially larger discontinuity than either isolated transition. These changes should not be added linearly because the measured output depends on the combined transmission and efficiency of the complete optical configuration.

The transition was therefore treated as an instrumental systematic rather than as a physical feature of the detector response. In the final measurements, 400 nm was treated as the first wavelength point of the post-transition monochromator configuration. The ultraviolet and visible scan regions were not assumed to form a continuous instrumental-output curve across this boundary, and separate slit-width settings were used for the two regions. The consequences for the reconstructed QE and the quality-control procedure are discussed in Sec. 6.2.2.

5.3.4 Lamp Warm-Up and Optical-Flux Stability

Before the PMT QE measurements, the influence of monochromator bandwidth and slit-width settings on the photodiode current was investigated. This test examined how the optical throughput changed when the monochromator was operated with different bandwidth settings or fixed physical slit widths. Under otherwise identical conditions, a smaller slit width is expected to transmit less light because it restricts the optical flux entering and leaving the monochromator. An unexpected result was observed during this comparison. The scan performed with the smallest fixed slit width of 0.04 mm produced a higher photocurrent than some scans obtained with larger effective slit widths, as shown in Fig. 5.14. Since this ordering cannot be explained by the slit width alone, it indicated that the measurements had been affected by a time-dependent change in the lamp output. A dedicated lamp-stability study was therefore performed.

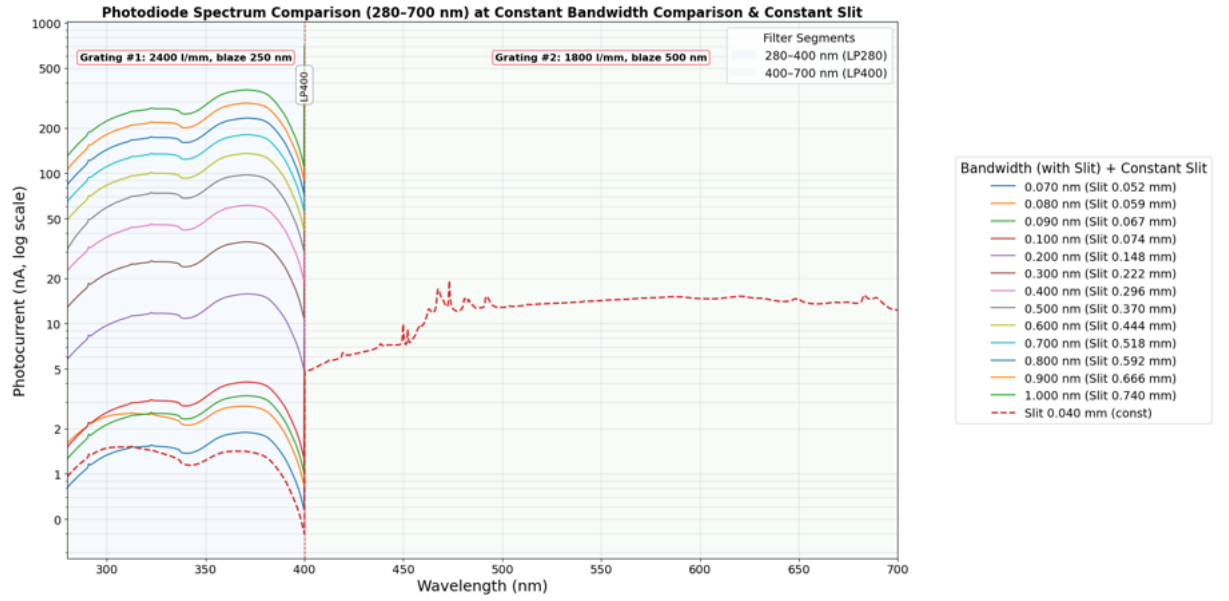


Figure 5.14: Photodiode spectra measured with different monochromator bandwidth and slit-width settings over 280 nm to 700 nm. The dashed red curve represents the scan with a fixed slit width of 0.04 mm. Its unexpectedly high photocurrent relative to measurements with larger effective slit widths indicated that the scans were affected by lamp-output drift.

The xenon-lamp stability was investigated using repeated measurements with the calibrated photodiode. The measured photocurrent is proportional to the optical flux delivered by the lamp-monochromator system. A change in lamp output between the photodiode and PMT scans would therefore introduce a systematic error into the QE reconstruction because the two detectors were measured sequentially rather than simultaneously.

The first stability series consisted of repeated scans over 280 nm to 700 nm with a constant slit width of 0.04 mm. The scans were separated by approximately 10 min. For each wavelength, the residual was calculated relative to the average current of all scans in the series.

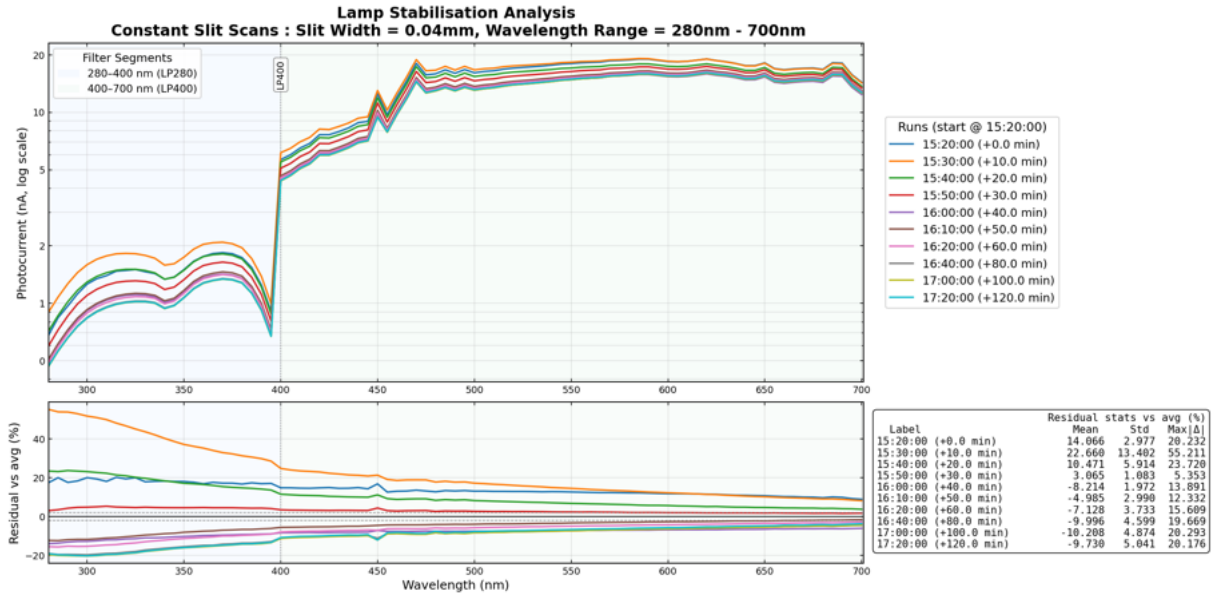


Figure 5.15: Repeated photodiode spectra recorded with a constant slit width of 0.04 mm. The upper panel shows the measured currents, while the lower panel shows the relative residual of each scan from the average spectrum. Before completion of the lamp warm-up, the maximum absolute residual reached approximately 55.2%, demonstrating that measurements taken during this period were strongly affected by time-dependent lamp output.

Figure 5.15 shows substantial differences between the spectra recorded during the earlier operating period. Before 90 min of warm-up, the maximum absolute residual reached approximately 55.2%. The effect was strongest at short wavelengths, where the photocurrent was lower, but a measurable offset remained across the visible region. The observed differences were therefore too large to be attributed to measurement scatter and showed that the lamp output had not yet reached a sufficiently stable operating condition.

For the purposes of this measurement campaign, the lamp output was considered sufficiently stable when the relative variation between repeated spectral scans remained within approximately 5% over the measured wavelength range. This threshold was used as an operational criterion for the present setup rather than as a manufacturer-specified stability limit.

A second series was used to characterize the lamp between 90 min and 150 min after switch-on. The same wavelength range and slit width were used so that the later scans could be compared directly without introducing an additional monochromator-setting dependence.

Between 90 min and 150 min, the scan-mean residuals ranged from approximately -4.51% to $+2.80\%$. The maximum absolute pointwise residual over the complete 280 nm to 700 nm range was 4.81%, compared with 55.2% during the earlier measurements. The RMS of the scan-mean residuals in the later interval was approximately 2.30%. The later measurements therefore satisfied the adopted 5% stability criterion, supporting a minimum lamp warm-up time of approximately 90 min.

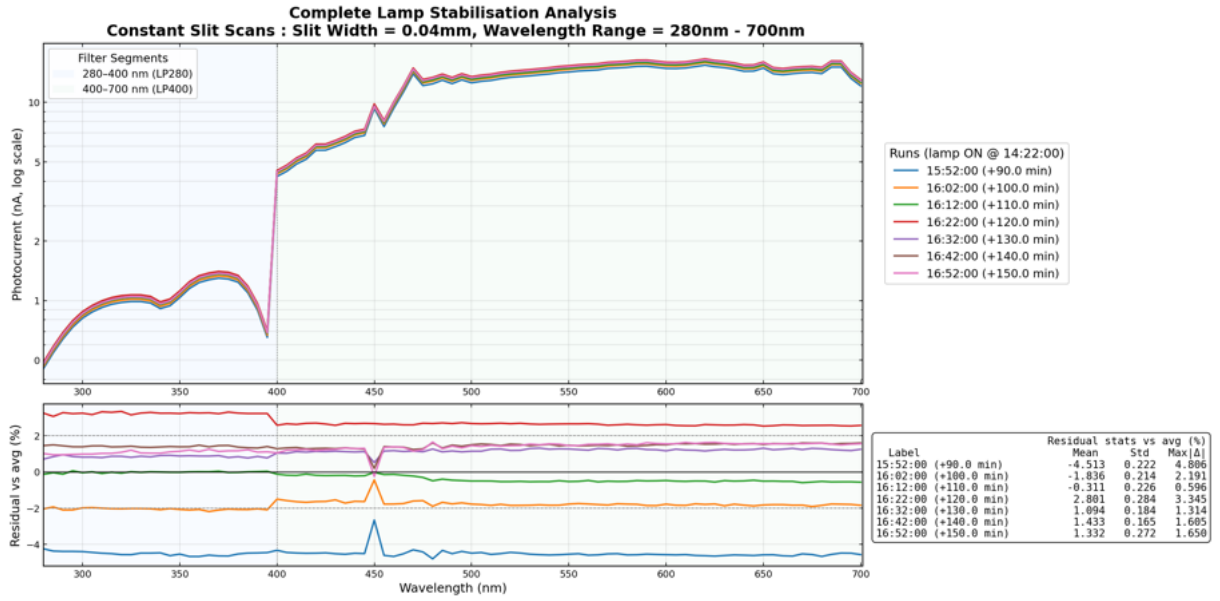


Figure 5.16: Photodiode spectra measured from 90 min to 150 min after lamp switch-on. Over the complete 280 nm to 700 nm interval, the maximum absolute residual was 4.81 %. The residual standard deviation within the individual scans ranged from approximately 0.165 % to 0.284 %, showing that the remaining variation was dominated by an overall flux offset rather than a wavelength-dependent change in spectral shape.

The small residual standard deviations within the individual later scans, ranging from 0.165 % to 0.284 %, show that the spectral shapes were reproducible once the warm-up period had elapsed. The remaining variation was mainly a wavelength-independent change in the overall optical-flux level. This distinction is important because a wavelength-dependent change could distort the reconstructed QE spectrum, whereas an overall normalization drift primarily changes its absolute scale.

The residual bound of 4.81 % was obtained over the complete measured wavelength range and therefore also provides a conservative upper bound for the scientifically relevant 300 nm to 500 nm interval. The later measurement series thus established a clear reduction in both the magnitude and wavelength dependence of the lamp drift.

A minimum lamp warm-up time of 90 min was therefore adopted before beginning the photodiode reference and PMT measurements. Scans obtained before this threshold were not used for the final QE reconstruction and were repeated after the required warm-up period. After 90 min, the wavelength-dependent residual remained within 4.81 % over the 300 nm to 500 nm interval. The remaining post-warm-up flux variation was included in the optical-flux systematic uncertainty because the PMT and photodiode measurements were not performed simultaneously.

5.3.5 Dark-Current Integration and Drift Treatment

Dark-current measurements were recorded as part of every scan in order to correct the measured photocurrents for electronic offsets, detector dark current, and slow baseline drift. The shutter position of the monochromator filter wheel was used for these measurements, so that the optical path was blocked without changing the detector position or cabling.

Before the final QE measurements, the PMTs were also tested for dark-current stabilisation. This was necessary because the PMTs were transported from storage to the light-tight box before measurement, during which they could be exposed to ambient light. After such exposure, the measured dark current does not immediately reach a stable baseline. Instead, it relaxes with time after the PMT is placed in darkness. If measurements are started too early, this relaxation

can appear as a false photocurrent offset and can directly affect the dark-current subtraction.

For this reason, the PMTs were placed inside the black box with the monochromator shutter closed, and the dark current was recorded for several minutes before the scan. The stabilisation behaviour was analysed by smoothing the measured dark-current time series and identifying the time after which the current remained within a stable band around the final mean. The relaxation can be described phenomenologically by an exponential approach to a stable value,

$$I_{\text{dark}}(t) = I_{\infty} + A \exp\left(-\frac{t}{\tau}\right), \quad (5.14)$$

or, more generally, by a two-component relaxation,

$$I_{\text{dark}}(t) = I_{\infty} + A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right), \quad (5.15)$$

where I_{∞} is the final dark-current level and τ_1, τ_2 are relaxation timescales. The fit was used only as a diagnostic description of the relaxation trend; the actual stabilised region was identified from the measured data.

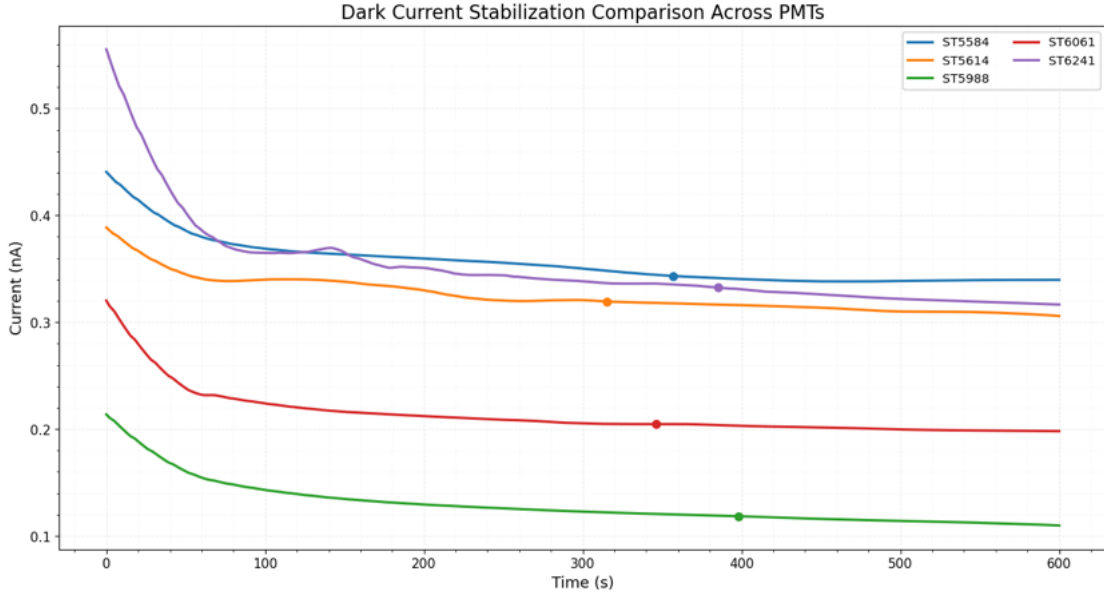


Figure 5.17: Dark-current stabilisation comparison across several PMTs after placing them in the light-tight box with the shutter closed. The curves show that the dark current decreases with time before reaching a slowly varying baseline. The stabilisation time differs between PMTs, motivating a waiting period before starting QE measurements.

The stabilisation criterion was based on the smoothed current trend $S(t)$. A current was considered stable when it remained close to the final dark-current mean and when its slope was sufficiently small over a sustained time interval. This condition can be written schematically as

$$|S(t) - I_{\infty}| \leq \Delta I_{\text{stab}}, \quad \left| \frac{dS}{dt} \right| \leq \epsilon_{\text{slope}}, \quad (5.16)$$

for a continuous interval of duration $\Delta t_{\text{sustain}}$. In the analysis, the stable region was the first sustained region satisfying the above conditions and were marked as the start of the stabilised dark-current interval. Figure 5.17 shows that the dark-current relaxation was not identical for all tested PMTs. Some tubes reached a stable level faster, while others showed a longer relaxation tail. From the comparison of the different PMT dark-current traces, the onset of stable behaviour was found to occur after several minutes. As a practical operational criterion, the earliest reliable

stabilisation time was estimated from the average behaviour of the tested PMTs and was taken to be approximately 360 s.

The example in Fig. 5.18 shows the detailed stabilisation analysis for PMT ST6241. In this case, the stabilised region began at approximately 385 s, with a stable mean current of about 0.322 nA. This is consistent with the general estimate of a stabilisation time of about 360 s. Therefore, a dedicated dark-current acquisition period of roughly 6 min was used before the scan, rather than assuming that the dark current was stable immediately after the PMT was placed in the box. Additional representative dark-current stabilisation examples for other PMTs are provided in Appendix A.1.

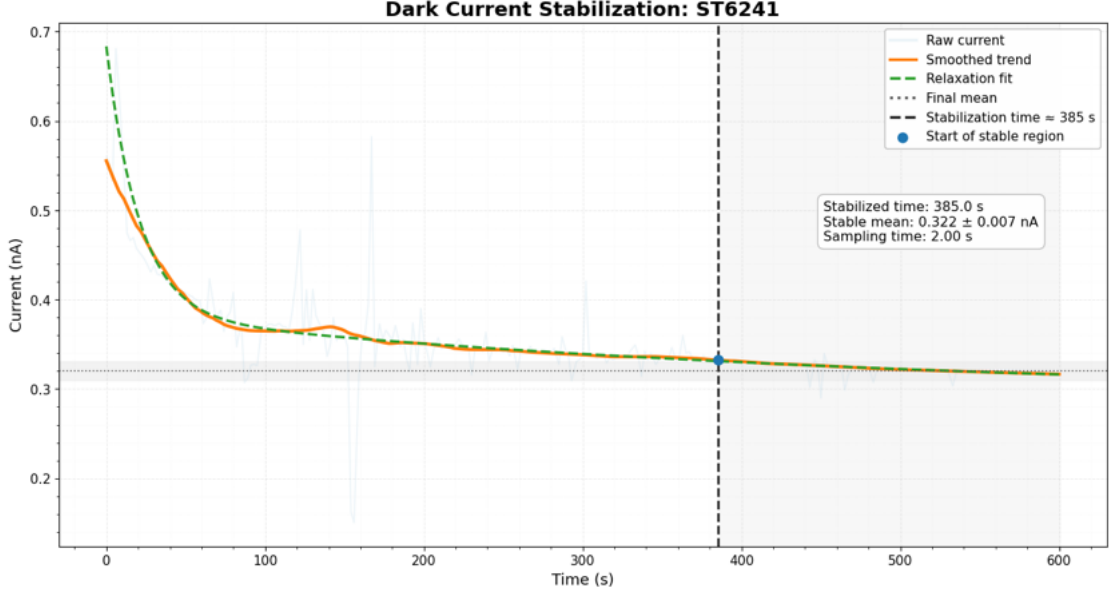


Figure 5.18: Example dark-current stabilisation analysis for PMT ST6241. The raw current is shown together with the smoothed trend and relaxation fit. The vertical dashed line marks the start of the stable region, identified at approximately 385 s. The final stable mean current is about 0.322 nA.

For the non-angular spectral QE measurements, a constant dark-current reference was calculated using the edge values of the raw dark-current blocks. Specifically, the last raw pre-dark value and the first raw post-dark value were averaged:

$$D_{\text{edge}} = \frac{1}{2} (D_{\text{pre,last}} + D_{\text{post,first}}). \quad (5.17)$$

The dark-corrected photodiode current was then calculated as

$$I_{\text{PD,corr}}(\lambda) = I_{\text{PD,meas}}(\lambda) - D_{\text{PD,edge}}. \quad (5.18)$$

For the PMT, the same subtraction was applied:

$$I_{\text{PMT,corr}}(\lambda) = I_{\text{PMT,meas}}(\lambda) - D_{\text{PMT,edge}} \quad (5.19)$$

For the angular measurements, the scan duration was longer and the dark-current correction was therefore treated as a time-dependent baseline. A global pre-dark block was recorded before the full angular sequence, and a final post-dark block was recorded after the last angular scan. The PMT dark baseline was interpolated linearly between these two anchors. For a scan point measured at time t , the baseline was

$$D(t) = D_{\text{pre}} + (D_{\text{post}} - D_{\text{pre}}) \frac{t - t_{\text{pre}}}{t_{\text{post}} - t_{\text{pre}}}, \quad (5.20)$$

where D_{pre} and D_{post} are the mean dark currents of the pre- and post-dark blocks, and t_{pre} and t_{post} are their representative timestamps.

The dark-corrected current for a general scan point can therefore be written as

$$I_{\text{corr}}(\lambda, \theta, t) = I_{\text{meas}}(\lambda, \theta, t) - D(t). \quad (5.21)$$

The uncertainty of the drift-corrected dark baseline was propagated from the uncertainties of the pre- and post-dark anchors. Defining

$$\alpha = \frac{t - t_{\text{pre}}}{t_{\text{post}} - t_{\text{pre}}}, \quad (5.22)$$

the dark-baseline uncertainty was calculated as

$$\sigma_D^2(t) = (1 - \alpha)^2 \sigma_{D,\text{pre}}^2 + \alpha^2 \sigma_{D,\text{post}}^2. \quad (5.23)$$

The total uncertainty of the dark-corrected current was then obtained by combining the signal-current uncertainty and the dark-baseline uncertainty:

$$\sigma_{I_{\text{corr}}}^2 = \sigma_{I_{\text{meas}}}^2 + \sigma_D^2(t). \quad (5.24)$$

This correction procedure allowed the same raw measurement files to support two levels of analysis. For shorter non-angular spectral scans, the edge-mean dark correction was sufficient and provided a simple baseline estimate using the nearest dark-current values around the scan. For longer angular scans, the time-dependent interpolation accounted for slow dark-current drift over the full measurement duration. The preliminary dark-stabilisation measurements also showed that the PMT should not be measured immediately after handling or light exposure.

5.3.6 Angular-Scan Procedure and Rotation-Stage Calibration

Angular-response measurements required the PMT to be rotated reproducibly relative to the fixed monochromator beam. The PMT was mounted on a horizontal motorized rotation stage controlled through a TCM-1110 stepper-motor controller. The optical path, iris position, and beam direction remained unchanged during the scan; only the PMT orientation was varied.

Before each angular scan, the PMT position was adjusted so that the beam illuminated the central region of the photocathode at the reference stage position. At this position, the beam was aligned approximately with the local surface normal at the photocathode centre. The corresponding stage position was defined operationally as 0° . Positive and negative rotations then moved the illuminated region away from the centre and towards opposite sides of the hemispherical photocathode.

The operational zero was determined from the mechanical alignment of the PMT and beam. It was therefore an experimental reference position rather than an exact determination of the true photocathode symmetry axis. Small residual offsets caused by mounting tolerances, beam displacement, or imperfect coincidence between the rotation axis and the PMT centre were evaluated later from the measured spatial-response symmetry, as described in Sec. 8.4.3.

The motor controller operates in internal position units rather than degrees. An empirical conversion factor was therefore determined before the angular measurements,

$$1^\circ \simeq 9400 \text{ internal units}. \quad (5.25)$$

For a requested angular displacement θ_{req} relative to the operational centre position, the corresponding motor displacement was calculated as

$$u_{\text{req}} = \theta_{\text{req}} u_{\text{deg}}, \quad u_{\text{deg}} = 9400, \quad (5.26)$$

where u_{deg} is the number of internal motor units per degree. The physical angle estimated from the controller readback was

$$\theta_{\text{act}} = \frac{u_{\text{act}}}{u_{\text{deg}}}, \quad (5.27)$$

where u_{act} is the measured motor displacement relative to the assigned central position.

The stage movement was accepted when the difference between the requested and read-back angles satisfied

$$|\theta_{\text{act}} - \theta_{\text{req}}| \leq \Delta\theta_{\text{tol}}, \quad (5.28)$$

with an angular tolerance of 0.15° . If this tolerance was not reached before the movement timeout, the measured read-back angle was still stored so that the later analysis could use the actual position rather than the requested value.

The angular scan was organized in angle blocks. At the beginning of each block, the shutter was closed and the stage was moved to the requested angular position. After the actual position had been read back, the shutter was opened and a complete wavelength scan was performed at that fixed angle. Increasing $|\theta|$ moved the illuminated region progressively away from the photocathode centre and towards the nominal active boundary.

For every wavelength point, the output file stored the angle-block index, requested angle, actual angle, wavelength, current statistics, slit-width values, and filter-wheel position. Recording the requested and measured angles separately allowed the spatial response to be reconstructed from the actual motor positions and made it possible to distinguish angular effects from temporal changes during the scan.

The initial and final 0° measurements returned the beam to the operational photocathode-centre position and served as internal reproducibility checks. Agreement between these spectra indicated that changes observed at other angles were associated mainly with the illuminated photocathode position rather than with drift during the measurement sequence.

A complete operational workflow for the angular QE measurement, including PMT mounting, central-position alignment, system checks, dark-current acquisition, stage movement, wavelength scanning, and photodiode reference measurement, is provided in Appendix A.2. The angular scans were saved automatically after each angle block; the corresponding file-recovery and autosave procedure is described in Appendix A.3.

5.4 Photodiode Calibration

The calibrated silicon photodiode was used as the reference detector for the PMT quantum-efficiency measurements. The detector was a Bentham DH-Si photodiode with serial number 38449/2. Its calibration certificate provides the wavelength-dependent spectral responsivity $R_{\text{PD}}(\lambda)$ in units of A W^{-1} over the range 250 nm to 1100 nm, with values tabulated in 5 nm steps.

The calibration was performed by comparison with a silicon-detector standard traceable to the Physikalisch-Technische Bundesanstalt, Germany's national metrology institute, using a monochromatic probe source and a double monochromator. The certificate reports a wavelength accuracy of ± 0.15 nm, while the relative responsivity uncertainty depends on the wavelength range [15].

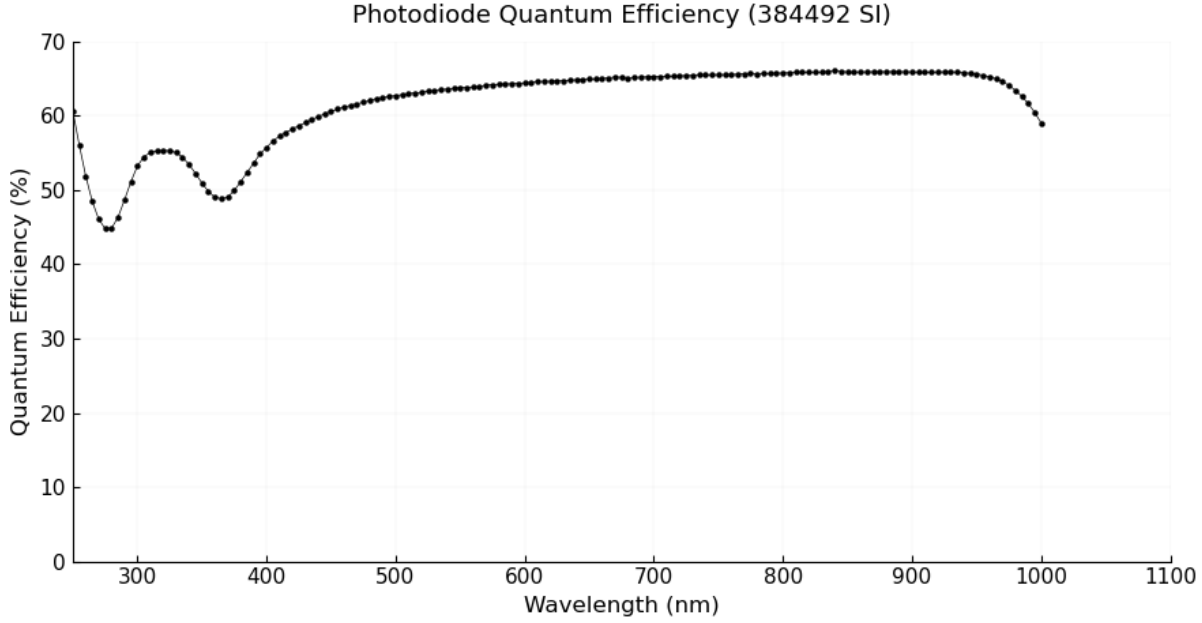


Figure 5.19: Quantum efficiency of the calibrated Bentham DH-Si photodiode, calculated from the manufacturer-provided spectral responsivity. The calibration covers the wavelength range from 250 nm to 1100 nm in 5 nm steps and provides the reference curve used in the PMT quantum-efficiency calculation.

The photodiode responsivity relates the measured current to the incident optical power through

$$I_{PD}(\lambda) = R_{PD}(\lambda) P_{opt}(\lambda). \quad (5.29)$$

Using the photon energy $E_\gamma = hc/\lambda$, the tabulated responsivity was converted into photodiode quantum efficiency according to

$$QE_{PD}(\lambda) = R_{PD}(\lambda) \frac{hc}{e\lambda}. \quad (5.30)$$

Here, h is Planck's constant, c is the speed of light, e is the elementary charge, and λ is expressed in metres.

Figure 5.19 shows the resulting photodiode quantum-efficiency curve. The photodiode QE lies approximately between 45 % and 65 % across much of the calibrated range, with a lower response in the near-ultraviolet region and a gradual decrease towards the longest wavelengths.

During the PMT analysis, the calibrated photodiode QE values were interpolated to the wavelengths used in the PMT scans. The reference-detector response was therefore evaluated at the same wavelengths as the measured PMT photocurrent.

5.5 Photomultiplier Quantum-Efficiency

The quantum efficiency of each PMT was determined relative to the calibrated silicon photodiode described in Section 5.4. At each wavelength, the PMT photocathode current was compared with the photodiode current measured using the same monochromator and iris settings. The calculation used the calibrated photodiode QE together with the dark-corrected detector currents.

Wavelength Scan and Monochromator Settings

Each PMT was scanned over the wavelength range from 280 nm to 700 nm. Two monochromator slit widths were used, as summarized in Table 5.1.

Table 5.1: Monochromator slit widths used for the PMT and photodiode wavelength scans.

Wavelength interval	Slit width
280 nm to 395 nm	0.310 mm
400 nm to 700 nm	0.120 mm

The two slit-width regions reduced the optical-throughput discontinuity associated with the grating and order-sorting-filter transition near 400 nm. The narrower slit at longer wavelengths also kept the PMT and photodiode currents within a suitable measurement range.

Dark-Current Correction

The measured detector currents contain both the light-induced photocurrent and a dark-current contribution. The corrected photodiode and PMT currents were calculated as

$$I_{\text{PD,corr}}(\lambda) = s_{\text{PD}} [I_{\text{PD,meas}}(\lambda) - D_{\text{PD}}(\lambda)], \quad (5.31)$$

$$I_{\text{PMT,corr}}(\lambda) = s_{\text{PMT}} [I_{\text{PMT,meas}}(\lambda) - D_{\text{PMT}}(\lambda)]. \quad (5.32)$$

Here, $I_{\text{PD,meas}}(\lambda)$ and $I_{\text{PMT,meas}}(\lambda)$ are the measured light currents. The quantities $D_{\text{PD}}(\lambda)$ and $D_{\text{PMT}}(\lambda)$ are the corresponding dark-current baselines.

The fixed polarity factors satisfy

$$s_{\text{PD}}, s_{\text{PMT}} \in \{-1, +1\}. \quad (5.33)$$

These factors place the PMT and photodiode currents on the same positive photocurrent convention. Their values are fixed by the detector wiring and must be applied consistently at every wavelength.

Photomultiplier Pre-Dark Current Baseline Correction

Two dark-current treatments were used because the earlier PMT scan files stored only the mean pre-dark and post-dark values. During the beginning of a pre-dark measurement, the PMT current could still be relaxing after previous possible illumination. The mean over the complete pre-dark interval was therefore corrected using the stable final part of the corresponding pre-dark trace.

The ratio between the complete pre-dark mean and the stable end-region mean was defined as

$$r_{\text{pre}} = \frac{D_{\text{pre,full}}}{D_{\text{pre,end}}}. \quad (5.34)$$

where $D_{\text{pre,full}}$ is the mean over the full pre-dark interval and $D_{\text{pre,end}}$ is the mean over its stable final region.

The corrected pre-dark value was then calculated as

$$D_{\text{pre,corr}} = \frac{D_{\text{pre,full}}}{r_{\text{pre}}}. \quad (5.35)$$

The PMT dark-current baseline used for the spectral scan was calculated from the corrected pre-dark value and the post-dark value:

$$D_{\text{PMT}} = \frac{D_{\text{pre,corr}} + D_{\text{post}}}{2}. \quad (5.36)$$

This additional correction was applied only to the PMT current. The photodiode dark-current treatment was left unchanged because the same relaxation after illumination was not observed for the calibrated photodiode.

Photomultiplier Quantum-Efficiency Calculation

The PMT and photodiode scans were performed sequentially using the same monochromator configuration and iris setting. The beam diameter was approximately 8 mm, which was smaller than the 10 mm x 10 mm active area of the photodiode. The complete beam was therefore intercepted during the photodiode reference measurement.

For the central PMT scans, the same beam was fully contained within the illuminated photocathode region. No detector-area or beam-overlap correction was applied.

The PMT quantum efficiency was calculated from the ratio of the dark-corrected photocathode current to the dark-corrected photodiode current:

$$\text{QE}_{\text{PMT}}(\lambda) = \frac{I_{\text{PMT,corr}}(\lambda)}{I_{\text{PD,corr}}(\lambda)} \text{QE}_{\text{PD}}(\lambda). \quad (5.37)$$

Here, $I_{\text{PMT,corr}}(\lambda)$ is the dark-corrected photocathode current, $I_{\text{PD,corr}}(\lambda)$ is the dark-corrected photodiode current, and $\text{QE}_{\text{PD}}(\lambda)$ is the calibrated photodiode quantum efficiency obtained from Eq. 5.30.

The complete calculation follows the sequence

$$R_{\text{PD}}(\lambda) \longrightarrow \text{QE}_{\text{PD}}(\lambda) \longrightarrow [I_{\text{PD,corr}}(\lambda), I_{\text{PMT,corr}}(\lambda)] \longrightarrow \text{QE}_{\text{PMT}}(\lambda).$$

The resulting QE values are dimensionless and are presented as percentages in the following analysis.

Wavelength-Dependent Quantum Efficiency

The extracted wavelength-dependent quantum efficiency of PMT ST5937 is shown in Fig. 5.20, together with the corresponding corrected PMT photocurrent. The PMT was operated at +450 V. The shaded region indicates the first wavelength segment, measured with a slit width of 0.310 mm, while the second segment above 400 nm was measured with a slit width of 0.120 mm.

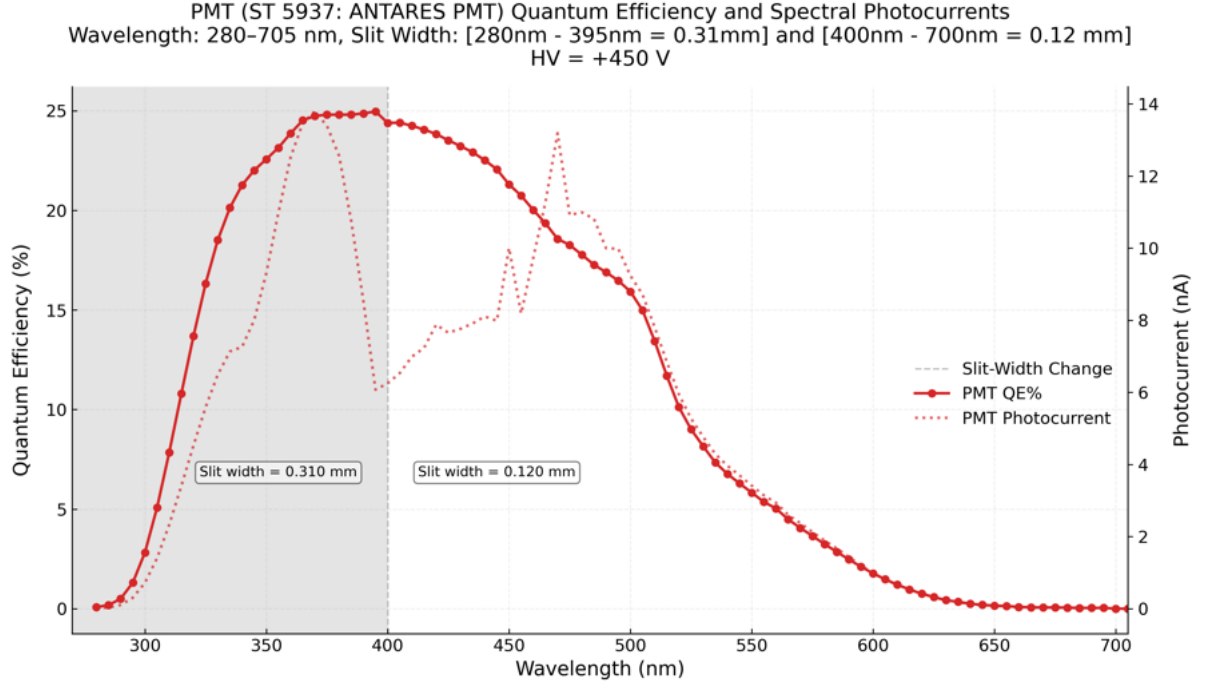


Figure 5.20: Corrected quantum efficiency and spectral photocurrent of PMT ST5937. The PMT pre-dark baseline was corrected using the stabilisation ratio before dark subtraction. The scan was performed with 0.310 mm slit width below 400 nm and 0.120 mm slit width above the transition.

The corrected QE curve shows a broad maximum in the near-UV/blue region, with a peak quantum efficiency of approximately 25%. The QE remains high between roughly 340 nm and 420 nm, and then decreases gradually toward longer wavelengths. This behaviour is consistent with the expected spectral response of a bialkali photocathode, where the sensitivity is strongest in the UV-blue region and falls toward the red part of the spectrum.

The dotted curve in Fig. 5.20 shows the corrected PMT photocurrent. Unlike the QE curve, the photocurrent still contains the wavelength dependence of the lamp spectrum, monochromator throughput, slit-width configuration, and PMT response. The QE calculation removes the reference optical-flux dependence by normalising the PMT photocurrent to the calibrated photodiode measurement. Therefore, the QE curve represents the detector response more directly than the raw photocurrent spectrum.

Uncertainty Propagation and Systematic Effects

The uncertainty of the extracted PMT quantum efficiency was evaluated from the uncertainties of the dark-corrected PMT current, the dark-corrected photodiode current, and the calibrated photodiode quantum efficiency. Other effects, such as lamp stability, slit-width reproducibility, alignment, and the 400 nm monochromator transition, were not subtracted point by point. Instead, they were treated as systematic limitations when interpreting the QE spectra.

For compact notation, the PMT quantum efficiency can be written as

$$Q(\lambda) = \frac{I_{\text{PMT,corr}}(\lambda)}{I_{\text{PD,corr}}(\lambda)} Q_{\text{PD}}(\lambda), \quad (5.38)$$

where $Q(\lambda) \equiv QE_{\text{PMT}}(\lambda)$ and $Q_{\text{PD}}(\lambda) \equiv QE_{\text{PD}}(\lambda)$. Assuming the PMT current, photodiode current, and photodiode calibration uncertainty are independent, the relative uncertainty is

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{I_{\text{PMT}}}}{I_{\text{PMT,corr}}}\right)^2 + \left(\frac{\sigma_{I_{\text{PD}}}}{I_{\text{PD,corr}}}\right)^2 + \left(\frac{\sigma_{Q_{\text{PD}}}}{Q_{\text{PD}}}\right)^2. \quad (5.39)$$

The current uncertainties include the statistical spread of photocurrent readings and the uncertainty of the dark-current baseline. For a dark-corrected current,

$$I_{\text{corr}} = I_{\text{meas}} - D, \quad (5.40)$$

the corresponding variance is

$$\sigma_{I_{\text{corr}}}^2 = \sigma_{I_{\text{meas}}}^2 + \sigma_D^2. \quad (5.41)$$

Table 5.2: Main uncertainty and systematic contributions relevant for the PMT quantum-efficiency extraction.

Source	Origin	Treatment
PMT current noise	Keithley Picoammeter readout noise and short-term current fluctuations	Propagated point-to-point
Photodiode current noise	Readout noise in the reference detector measurement	Propagated point-to-point
Dark-current baseline	Pre-dark/post-dark estimation and possible dark-current drift	Corrected and propagated
Photodiode calibration	Manufacturer-provided responsivity uncertainty	Reference-scale uncertainty
Lamp-output stability	Residual lamp drift between photodiode and PMT scans	Optical-flux systematic
Slit-width reproducibility	Difference between target and achieved monochromator slit widths	Optical-throughput systematic
400 nm transition	Grating and filter-wheel change in the monochromator	Local systematic near transition
Alignment and beam position	Detector placement and beam overlap with active area	Global or slowly varying systematic

For earlier measurements where only summary dark-current values were available, the effect of the pre-dark correction was treated as a systematic contribution by comparing corrected and uncorrected QE values.

The entries in Table 5.2 describe systematic effects that were not subtracted point by point, but were used to guide the interpretation of the spectra. Smooth wavelength-dependent features that were reproducible between scans were interpreted as PMT response, whereas localized features near known instrumental boundaries, especially around 400 nm, were treated conservatively as possible residual systematics.

The propagated uncertainties describe point-to-point variations of the QE curve. Lamp stability, slit-width reproducibility, alignment, and the 400 nm transition were treated as residual systematic limitations when interpreting individual spectral features.

Chapter 6

Data Processing and Measurement-Quality Assessment

6.1 Overview of the Measured Dataset

The analysis used quantum-efficiency measurements of 124 extracted ANTARES PMTs from detector Lines 4 and 8, together with the reference PMT TM0007. For each measured PMT, the analysis table linked the laboratory QE spectrum to the available ANTARES metadata, including detector line, storey position, PMT serial number, optical-module status, and high-voltage failure information where available.

The starting point for this mapping was the ANTARES optical-module status sheet. During the PMT extraction campaign, this information was extended with extraction-related details. Not every optical module could be used for laboratory QE measurements: some modules were damaged, water-affected, or could not be opened cleanly because of hardened optical gel, making PMT extraction impossible or unsafe. In addition, one extracted PMT listed in the measurement-control sheet could not be measured because of a broken base.

A separate QE PMT list was then prepared as the measurement-control and analysis sheet. It connected each extracted PMT to the corresponding laboratory measurement files, including the PMT spectral file and the photodiode reference file where applicable. The list also included a representative peak-region QE value near 370 nm, which was used for fast data-control checks because the measured PMT spectra typically reach their maximum sensitivity close to this region.

This link allowed the QE spectra to be studied both as a measured PMT population and as recovered detector components with known ANTARES provenance.

6.2 Why Quality Control is Required Before Aging Analysis

Before comparing PMTs for aging, the spectra had to be checked for measurement artifacts. A low QE value is not automatically evidence of a degraded photocathode: it can also result from dark-current subtraction, low photocurrent, optical-throughput changes, or the monochromator transition near 400 nm. The QC step was therefore used to separate spectra suitable for aging interpretation from spectra that first require inspection or retesting.

6.2.1 Measurement Artifacts that Mimic Aging

A physically meaningful PMT QE spectrum is expected to vary smoothly with wavelength. The exact amplitude can differ from tube to tube, but abrupt wavelength-localized jumps,

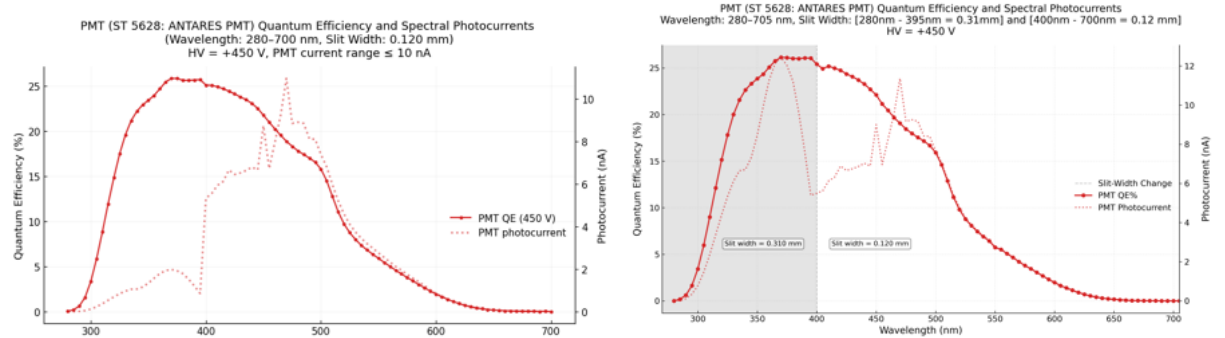
isolated kinks, or strong roughness are not expected from normal photocathode aging alone. Such features are more likely to originate from the measurement chain, for example from the monochromator transition, dark-current subtraction, insufficient photocurrent, or small changes in optical alignment.

The main risk is simple: an instrumental feature can look like PMT degradation. A reduced QE curve may indicate real photocathode loss, but it may also result from an incorrect dark-current baseline or low-current sensitivity at the spectral edges. A sharp step near 400 nm is also more likely connected to the monochromator transition than to the photocathode itself. For this reason, spectra with strong local distortions were flagged before the aging analysis.

6.2.2 Slit-Width Transition Effects

The standard spectral QE measurements were divided into two slit-width regions. The wavelength range from 280 nm to 395 nm was measured with a slit width of 0.310 mm, while the range from 400 nm to 700 nm was measured with a slit width of 0.120 mm. The wider ultraviolet slit increased the detector currents in the region where the monochromator output was comparatively low. The narrower slit was retained above 400 nm, where the available optical intensity was already sufficient.

The slit width determines both the monochromator bandwidth and the transmitted optical intensity. In the MSH-300 monochromator, the entrance and exit slits define the wavelength interval reaching the detector and the optical throughput of the system [42]. The selected slit width can therefore affect the QE reconstruction through two competing effects. A narrow slit provides a smaller spectral bandwidth but can produce currents that are more sensitive to dark-current subtraction and baseline fluctuations. A wider slit increases the measured current and reduces this relative baseline contribution, but also increases the wavelength interval contributing to each measurement point.



(a) Constant slit width of 0.120 mm over the complete wavelength range. (b) Segmented configuration using 0.310 mm below 400 nm and 0.120 mm from 400 nm onward.

Figure 6.1: Comparison of the reconstructed QE and detector photocurrents for PMT ST5628 using constant and segmented slit-width configurations. The constant 0.120 mm setting produces substantially lower ultraviolet photocurrents, increasing the sensitivity of the reconstructed QE to dark-current subtraction. The segmented configuration increases the ultraviolet signal while retaining the same 0.120 mm setting in the visible region.

The relevant comparison in Fig. 6.1 is the reconstructed QE rather than the relative size of the two photocurrent regions. Above 400 nm, both measurements use the same slit width and provide a consistency check between the scans. In the ultraviolet region, the constant 0.120 mm scan produces lower PMT and photodiode currents. The dark-current correction consequently represents a larger fraction of the measured signal, so small baseline variations have a greater influence on the ratio used to reconstruct the QE.

The ultraviolet result obtained with the constant narrow slit is therefore the more bias-sensitive of the two measurements. The segmented configuration raises both detector currents and reduces

the relative influence of the dark-current subtraction. The comparison does not show a systematic QE displacement that would indicate a larger bias from the wider ultraviolet slit. The segmented configuration was therefore adopted for the standard measurements because it provided the more reliable ultraviolet QE reconstruction.

The region around 400 nm requires separate consideration because it is both the slit-width boundary and the wavelength at which the monochromator changes its grating and filter configuration. The photodiode-only investigation of this instrumental transition is presented in Sec. 5.3.3. The analysis here determines whether the configuration change remains visible after the PMT current is normalized to the calibrated photodiode response.

A dedicated forced-setting comparison was performed from 390 nm to 410 nm. The slit width was fixed at 0.120 mm, and the complete interval was measured using Grating 1 / Filter 2 and Grating 2 / Filter 3. Keeping the slit width fixed separates the grating and filter dependence from the slit-width change.

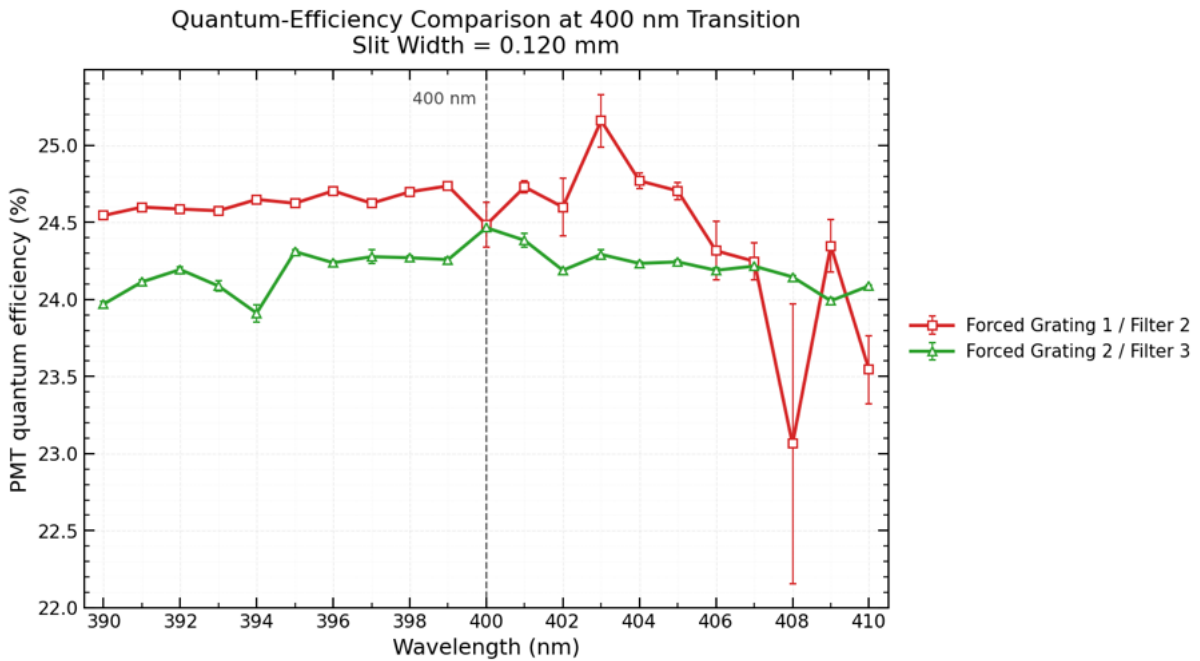


Figure 6.2: Reconstructed PMT QE between 390 nm and 410 nm for Grating 1 / Filter 2 and Grating 2 / Filter 3 at a fixed slit width of 0.120 mm. At 400 nm, both configurations give a QE of approximately 24.45 %. The absolute difference remains below approximately one percentage point over most of the investigated interval.

Figure 6.2 shows that the two monochromator configurations give closely matching QE values over most of the tested interval. In particular, the reconstructed values at 400 nm are practically identical. The agreement indicates that the change in monochromator throughput is common to the PMT and photodiode measurements and is largely removed by the relative QE calculation.

The raw detector currents provide a substantially different picture. As shown in Fig. 6.3, both the PMT and photodiode currents depend strongly on the selected grating and filter combination.

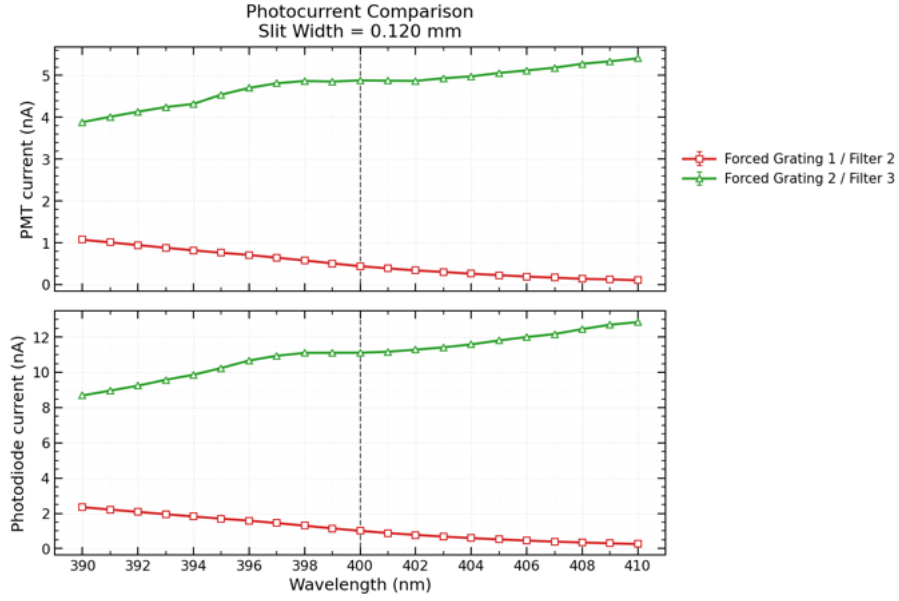


Figure 6.3: PMT and photodiode photocurrents measured between 390 nm and 410 nm for the two forced monochromator configurations at a fixed slit width of 0.120 mm. At 400 nm, the PMT current changes from approximately 0.43 nA to 4.9 nA, while the photodiode current changes from approximately 1.0 nA to 11.1 nA.

At 400 nm, changing from Grating 1 / Filter 2 to Grating 2 / Filter 3 increases the PMT current by a factor of approximately 11.4. The photodiode current increases by a similar factor of approximately 11.1. The delivered optical intensity therefore changes by about one order of magnitude, but the PMT and photodiode responses scale together. Their ratio, from which the PMT QE is reconstructed, consequently remains nearly unchanged.

The residual difference between the two QE reconstructions is shown in Fig. 6.4.

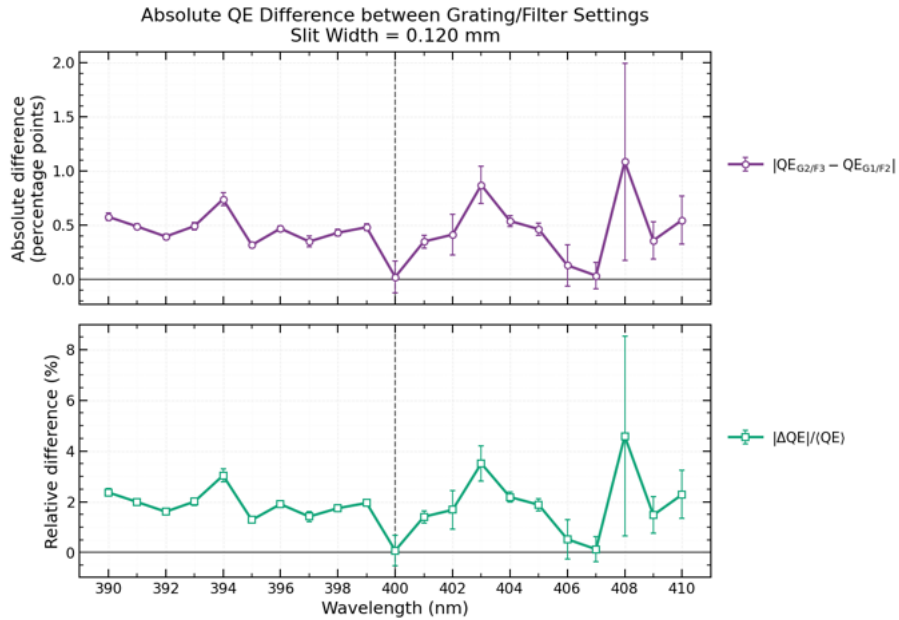


Figure 6.4: Absolute and relative differences between the reconstructed QE values obtained with the two forced grating and filter configurations. The absolute difference is predominantly below approximately one percentage point, and the relative difference is generally at the level of a few percent. At 400 nm, the difference is consistent with zero within the measurement uncertainty.

At 400 nm, the absolute difference between the two reconstructed QE values is approximately

0.02 percentage points, corresponding to a relative difference of approximately 0.1 %. Across most of the interval from 390 nm to 410 nm, the absolute difference remains below approximately one percentage point and the relative difference remains at the level of a few percent. The largest nominal difference occurs near 408 nm, where the uncertainty is also substantially larger. This point does not establish a reproducible configuration-dependent QE shift.

The forced-setting comparison therefore demonstrates that the photodiode normalization removes most of the monochromator-throughput change. The large raw-current difference at the transition is instrumental and does not appear as a comparable bias in the reconstructed QE. The remaining spread defines the scale of the localized systematic uncertainty in this wavelength region.

The slit-width and grating/filter studies address different effects. The wider ultraviolet slit reduces the susceptibility of the QE reconstruction to low-current baseline corrections, while the forced-setting study tests whether the monochromator configuration itself biases the normalized QE. Neither test indicates that the transition produces a dominant broadband QE bias. Nevertheless, the simultaneous change in slit width and optical configuration makes the region around 400 nm more sensitive to localized measurement artifacts.

The 400 nm boundary was therefore retained as a dedicated quality-control interval. Localized steps, kinks, or slope changes near this boundary were treated as possible instrumental effects and were not used independently as evidence of PMT aging. The aging interpretation was instead based on stable broadband spectral behaviour away from the monochromator transition.

6.2.3 Dark-Current Drift and Low-Current Sensitivity

As discussed in Sec. 5.3.5, dark-current subtraction is required before the PMT photocurrent can be used for QE reconstruction. The dark-current reference was chosen close to the scan interval to avoid large reconstructed-QE changes from small dark-current fluctuations, especially in low-current wavelength regions.

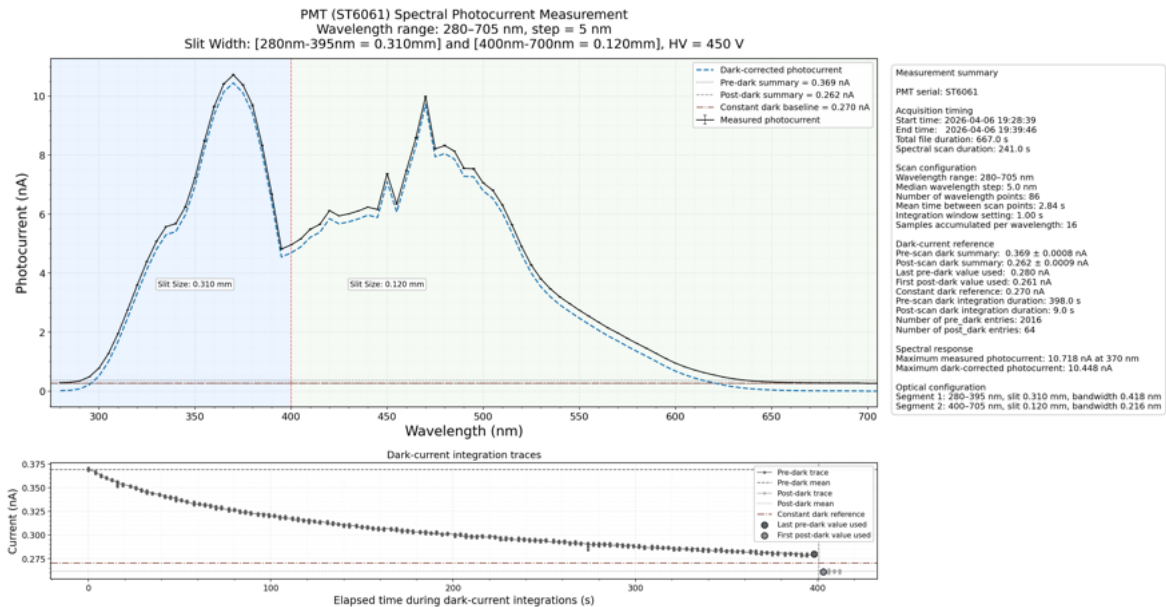


Figure 6.5: Example of dark-current treatment for the spectral photocurrent measurement of PMT ST6061. The upper panel shows the measured and dark-corrected photocurrent spectrum, while the lower panel shows the pre-dark and post-dark integration traces. The decrease of the pre-dark current demonstrates why the dark-current reference should be chosen close to the spectral scan interval.

Figure 6.5 illustrates this effect for PMT ST6061. The pre-dark current changes during the integration period, showing that a simple average over the full dark-current block may not always

represent the baseline closest to the illuminated scan. For this reason, the later analysis used dark-current values close to the scan interval, as described in Sec. 5.3.5.

In the quality-control context, low QE values were not interpreted as evidence of PMT aging by themselves. They were considered reliable only when the dark-current behaviour was stable and the corresponding spectral shape remained physically plausible.

6.2.4 Iris-Opening and Photocurrent-Flux Tests

Two control measurements were performed with PMT ST6352. The first examined the influence of the iris opening on the photodiode reference measurement. The second examined whether the reconstructed QE changed when the optical intensity and PMT photocurrent were varied through the monochromator slit settings.

The standard iris diameter was 8 mm. This setting was selected because the calibrated photodiode has an active area of 10 mm by 10 mm. Restricting the beam to approximately 8 mm kept the illuminated region within the photodiode area and reduced the risk of beam clipping at the detector boundary. This was important because the QE calculation assumes that the photodiode current represents the optical flux incident on the PMT.

A comparison measurement was performed with the iris opened to 12 mm. The PMT photocathode is considerably larger than the active area of the photodiode. A wider beam could therefore remain fully incident on the PMT while extending beyond the photosensitive area of the photodiode. In that case, the photodiode would not measure the complete optical flux received by the PMT, which could affect the reconstructed QE. The 12 mm measurement was therefore used as a control of the photodiode illumination geometry rather than as an alternative standard configuration.

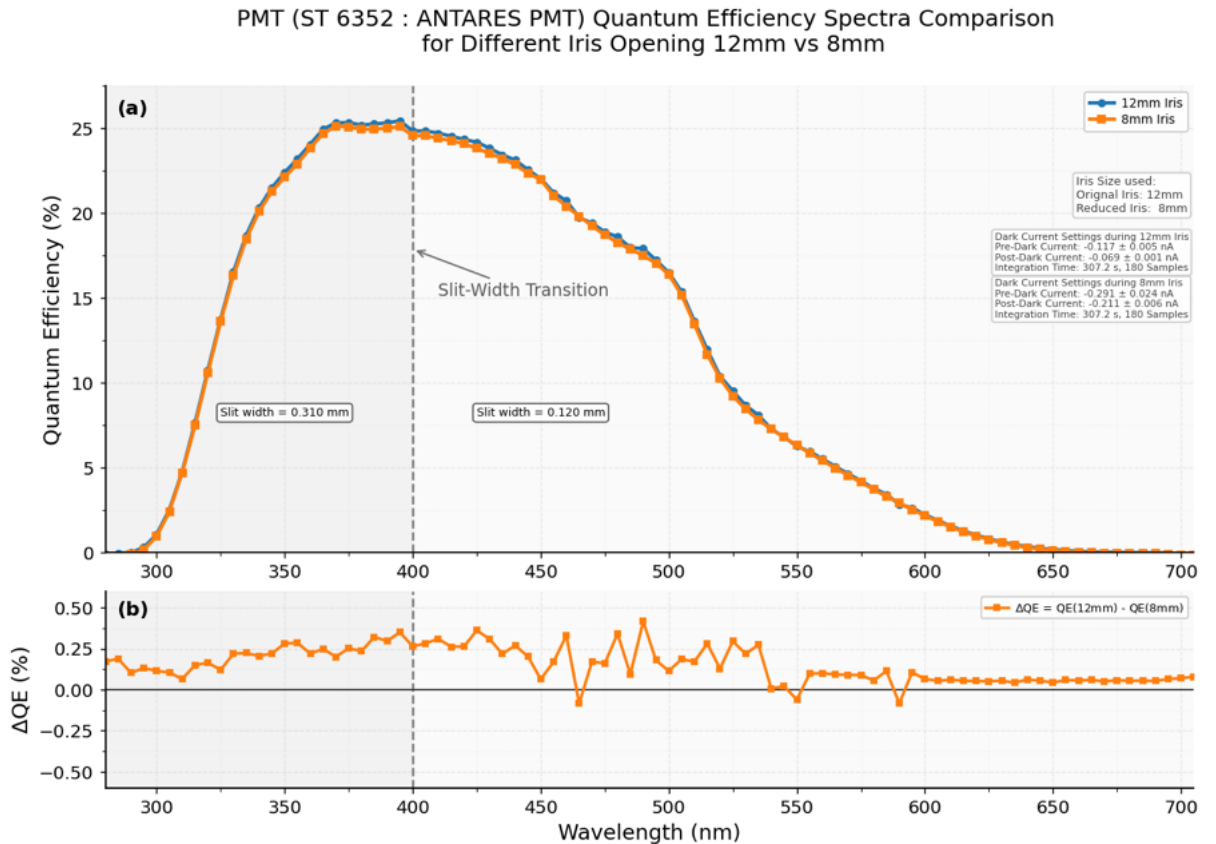


Figure 6.6: Comparison of the reconstructed QE of PMT ST6352 using iris openings of 12 mm and 8 mm. The comparison tests the influence of the photodiode illumination geometry on the QE reconstruction.

Figure 6.6 compares the reconstructed QE obtained with the two iris settings. The overall spectral behaviour is reproduced in both measurements, while the remaining differences indicate the sensitivity of the normalization to the selected beam diameter. The 8 mm iris was retained for the standard measurements because this configuration kept the beam within the calibrated photodiode area.

A separate control measurement was performed to examine the dependence of the QE reconstruction on optical intensity. In this test, the iris remained at the standard 8 mm setting so that the photodiode illumination geometry was unchanged. The monochromator slit-width and photocurrent-limit settings were varied to change the amount of light reaching the detectors.

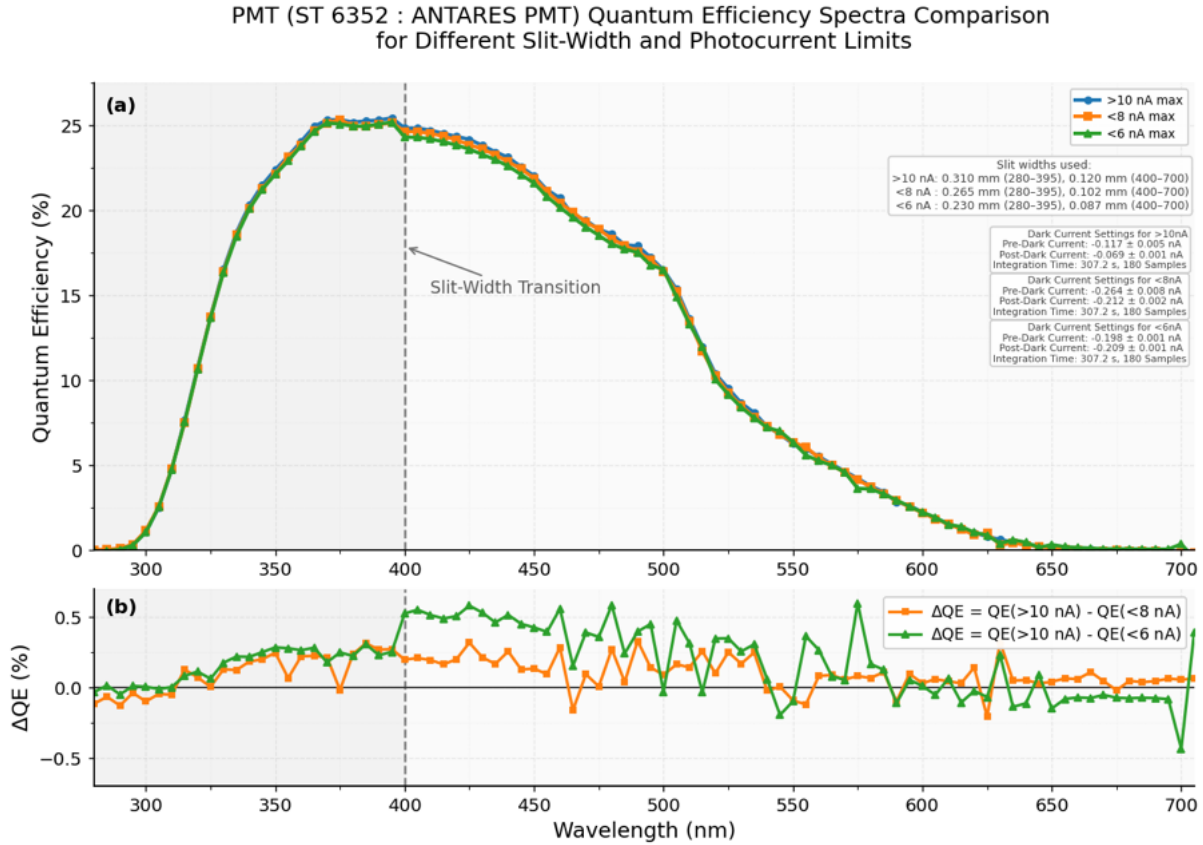


Figure 6.7: Comparison of the reconstructed QE of PMT ST6352 for different slit-width and photocurrent-limit settings, with the iris retained at 8 mm.

As shown in Fig. 6.7, the principal wavelength-dependent QE response is reproduced for the tested optical-intensity settings. The largest differences occur near the monochromator transition around 400 nm and in wavelength regions where the measured photocurrent is lower. These regions are more sensitive to throughput changes and measurement uncertainty.

The two control measurements address different systematic effects. The iris-opening comparison tests whether the photodiode collects the complete reference beam, whereas the slit-setting comparison tests the stability of the relative PMT-to-photodiode response when the optical flux is changed without altering the beam geometry. Based on these measurements, the 8 mm iris was retained for all standard photodiode and PMT scans. Differences associated with the 400 nm transition or low-photocurrent regions were considered during the quality-control evaluation.

6.3 Traditional Quality-Control

A simple quality-control approach would be to inspect each QE spectrum visually and compare its shape with the expected response of the Hamamatsu R7081-20. Spectra with abrupt jumps, isolated spikes, strong roughness, unusual slope changes, or abnormal low response could then be marked for further inspection. Peak or band-averaged QE values, for example in the 300–500 nm range, could also be used as compact threshold-based checks of the overall photon-conversion response.

These checks are useful for identifying obvious failures, but they are not sufficient for this dataset. More than one hundred extracted PMTs had to be compared consistently, and a low QE value and a distorted spectral shape are not the same problem. A smooth but globally reduced spectrum may indicate real photocathode loss, while a spectrum with a local kink or discontinuity may instead point to a measurement artifact. The final quality-control strategy therefore used automated population-based checks, rather than relying only on visual inspection or fixed QE thresholds.

6.4 Unsupervised Machine Learning for Quality Control

The quality-control procedure was implemented as an unsupervised analysis because no labelled training set of acceptable, degraded, and measurement-suspect PMTs was available. Instead, the measured PMT population itself was used to define the expected spectral behaviour. Each PMT spectrum was then ranked according to how strongly it differed from this population behaviour.

The unsupervised method was used as a first filtering step: spectra with unusual shapes were flagged before they entered the aging analysis. Manual inspection remained useful for understanding individual spectra, but the automated step made the initial comparison reproducible across the full PMT population.

Each PMT spectrum was treated as one data vector on a common wavelength grid. The pipeline combined robust population statistics, shape-based features, PCA reconstruction error, and an Isolation Forest anomaly score. The Isolation Forest was used to identify spectra that separate quickly from the rest of the population under repeated random feature splits, which is the basic idea behind its anomaly score. The final result remained interpretable because the machine-learning scores were combined with physical quantities such as boundary steps, kinks, roughness, and low-QE behaviour.

The corrected QE spectra were linearly interpolated onto a common wavelength grid extending from 280 nm to 700 nm in 5 nm steps. Values outside the measured wavelength range were not extrapolated. The corrected-QE column was used for the final analysis, and TM0007 was processed together with the extracted-PMT spectra so that all 125 spectra underwent the same automated procedure.

6.4.1 Population Median and MAD Reference

The first step was to define a robust reference spectrum for the measured PMT population. Since all measured tubes were of the same PMT model, their QE curves were expected to have a similar wavelength dependence, even if their absolute QE values differed. Spectra that deviate strongly from this population behaviour were therefore treated as possible anomalies.

For each wavelength point λ_j on the common grid, the median QE of the PMT population was calculated,

$$\tilde{Q}(\lambda_j) = \text{median}_i [Q_i(\lambda_j)], \quad (6.1)$$

where $Q_i(\lambda_j)$ is the QE of the i -th PMT at wavelength λ_j . The median was used instead of the mean because it is less sensitive to outliers, which is important when the dataset itself may contain degraded or measurement-suspect spectra.

The spread around the median was described using the **Median Absolute Deviation (MAD)**,

$$\text{MAD}(\lambda_j) = \text{median}_i \left[\left| Q_i(\lambda_j) - \tilde{Q}(\lambda_j) \right| \right]. \quad (6.2)$$

Each PMT spectrum was then compared with the population reference using a robust residual,

$$z_i(\lambda_j) = \frac{\left| Q_i(\lambda_j) - \tilde{Q}(\lambda_j) \right|}{\text{MAD}(\lambda_j) + \epsilon}, \quad (6.3)$$

where ϵ is a small numerical constant used to avoid division by zero. Large residuals mark wavelength regions where one spectrum differs strongly from the measured population.

Two residual-based quantities were used. The first was a global deviation score over the full wavelength range. The second was a boundary-region score around 400 nm, where the slit-width and monochromator transition occurs. This boundary score was included because the systematic studies showed that this wavelength region is especially sensitive to instrumental effects.

6.4.2 Shape-Based Anomaly Features

After defining the MAD reference, additional shape-based features were extracted from each QE spectrum. These features were chosen to identify spectral behaviour that is unlikely to result from smooth photocathode aging alone. Spectra with strong local distortions were flagged before being used for aging interpretation.

The first feature was the behaviour near the 400 nm transition region. A strong localized deviation around this wavelength can indicate a slit-width or monochromator-related artifact rather than a true PMT effect. The residuals around 400 nm were therefore treated separately from the global residuals.

A direct boundary-step metric was also calculated. The QE values on the left and right sides of the 400 nm transition were fitted locally with straight lines. The two fits were evaluated at 400 nm, and their difference was used as an estimate of the discontinuity,

$$\Delta Q_{400} = Q_{\text{right}}(400 \text{ nm}) - Q_{\text{left}}(400 \text{ nm}). \quad (6.4)$$

A large value of ΔQ_{400} indicates a sudden step at the transition wavelength. Since a real QE spectrum should vary smoothly, such a step was treated as a possible measurement artifact.

The second feature was local curvature. Sharp kinks were identified using the maximum absolute second derivative of the QE curve,

$$C_i = \max_{\lambda} \left| \frac{d^2 Q_i(\lambda)}{d\lambda^2} \right|. \quad (6.5)$$

The curvature values were compared using a robust z-score, and spectra with unusually high curvature were marked as kink candidates.

The third feature was the total variation,

$$TV_i = \sum_j |Q_i(\lambda_{j+1}) - Q_i(\lambda_j)|. \quad (6.6)$$

This quantity measures the accumulated point-to-point variation across the spectrum. Smooth curves have moderate total variation, while noisy or oscillatory curves produce larger values. It was therefore used as a roughness indicator.

Finally, a soft physical range check was applied. Clearly unrealistic QE values, for example far below zero or far above the expected range, were treated as possible reconstruction or file-level problems. This check was kept soft because small negative values can occur in low-current regions after dark-current subtraction.

Together, these features describe whether a spectrum is suitable for aging interpretation. They do not by themselves prove aging; they identify spectra that require caution before physical interpretation.

6.4.3 PCA Reconstruction Error

Principal Component Analysis (PCA) was used to identify spectra that do not follow the dominant wavelength-dependent shape of the measured population [27, 40]. Each interpolated QE spectrum was represented as a vector on the common wavelength grid,

$$\mathbf{z}_i = [z_i(\lambda_1), z_i(\lambda_2), \dots, z_i(\lambda_N)]. \quad (6.7)$$

Before fitting the PCA model, missing grid values were replaced by the wavelength-wise population median. If a wavelength column contained no finite values, the global median of the QE matrix was used as a fallback. The resulting matrix was transformed using robust median and interquartile-range scaling.

A two-pass procedure was used to reduce the influence of strongly unusual spectra on the PCA reference model. First, the Euclidean distance of each robustly scaled spectrum from the component-wise median spectrum was calculated. The closest 85% of the spectra, corresponding to $\lceil 0.85N \rceil$ spectra, were retained as an approximate central population. For the $N = 125$ processed spectra, this produced an inlier set of 107 spectra.

PCA was then fitted to this central subset using the exact full singular-value-decomposition solver. The number of retained components was selected automatically as the minimum required to explain at least 98% of the variance of the inlier set. Whitening was not applied.

Every spectrum was projected into the resulting PCA space and reconstructed. Since the model was fitted after robust scaling, the reconstruction error was calculated in the scaled space as

$$E_i^{\text{PCA}} = |\mathbf{z}_i - \hat{\mathbf{z}}_i|_2, \quad (6.8)$$

where $\mathbf{z}_i$ is the robustly scaled spectrum and $\hat{\mathbf{z}}_i$ is its PCA reconstruction. A large reconstruction error indicates spectral information that is not well represented by the dominant population shape.

6.4.4 Isolation Forest

An Isolation Forest was used as an independent unsupervised anomaly indicator [32, 40]. Unlike the PCA model, which operated on the complete interpolated QE spectra, the Isolation Forest was fitted to twelve engineered shape and quality-control features:

- PCA reconstruction error;
- global median–MAD residual;
- residual in the 390 nm to 410 nm boundary region;
- absolute boundary-step magnitude;
- absolute robust curvature score;
- total spectral variation;
- peak wavelength;
- spectral full width at half maximum;
- ultraviolet-to-visible integrated-response ratio;
- slope over 450 nm to 550 nm;
- slope over 550 nm to 650 nm;
- long-wavelength response change over 580 nm to 700 nm.

The method repeatedly partitions the multidimensional feature space using randomly selected features and split values. Spectra that are isolated after fewer partitions receive more anomalous scores. In this way, the Isolation Forest identifies unusual combinations of spectral properties that may not be captured by a single quality-control metric or by the dominant PCA representation alone.

Missing feature values were replaced by the median of the corresponding feature, and the resulting feature matrix was robustly scaled to prevent features with larger numerical ranges from dominating the analysis. The Isolation Forest was configured with 500 trees, automatic contamination and sample-size settings, all available features, sampling without replacement, and a fixed random seed of 42. For the dataset of 125 spectra, the automatic sample-size setting used all 125 spectra in the construction of each tree.

The anomaly quantity used in the hybrid score was the negative of the Isolation Forest decision function, so that larger values represented more unusual spectra. This quantity was converted to a population percentile rank and combined with the PCA reconstruction error and the explicit spectral-shape indicators.

The Isolation Forest therefore provided a complementary multivariate assessment of each spectrum. PCA quantified deviations from the dominant spectral population, while the Isolation Forest identified unusual combinations of boundary behaviour, curvature, spectral width, slopes, and long-wavelength response. Combining these methods produced a more complete and reproducible anomaly ranking than either approach alone, while the individual features retained a direct physical connection to the experimental systematics.

6.5 Quality-Control Scoring and Results

The extracted spectral features, PCA reconstruction error, and Isolation Forest anomaly score were combined into an automated ranking used to identify spectra for manual inspection. The ranking was intended as a quality-control aid; no PMT was rejected solely on the basis of the automated score.

Spectral shape and QE level were evaluated separately because they describe different properties. A spectrum may have a low but smooth response, while another spectrum with a typical QE level may contain discontinuities, unstable dark-current subtraction, or acquisition-dependent distortions.

All continuous quantities were converted to percentile ranks over the processed population, with values between 0 and 1. Larger ranks correspond to more anomalous behaviour. The shape-anomaly score was defined as

$$S_{\text{shape}} = 0.35R_{\text{PCA}} + 0.25R_{\text{IF}} + 0.15R_{400} + 0.10I_{\text{kink}} + 0.10R_{\text{TV}} + 0.05I_{\text{range}}, \quad (6.9)$$

where R_{PCA} , R_{IF} , R_{400} , and R_{TV} are the percentile ranks of the PCA reconstruction error, Isolation Forest anomaly score, residual in the 390 nm to 410 nm boundary region, and total spectral variation, respectively. The quantities I_{kink} and I_{range} are binary indicators with values of 0 or 1.

A kink was flagged when the absolute robust curvature score exceeded 7. The physical-range indicator was set when the first percentile of a spectrum fell below -3% QE or its 99th percentile exceeded 55% QE. The weights in Eq. (6.9) were chosen empirically to give the largest influence to population-level shape deviations while retaining sensitivity to local discontinuities and unphysical values. The score is therefore a review-ranking quantity rather than a physical measure of PMT degradation.

The low-QE score was defined separately as

$$S_{\text{low}} = 0.10(1 - R_{\text{peak}}) + 0.20(1 - R_{300-500}), \quad (6.10)$$

where R_{peak} and $R_{300-500}$ are the percentile ranks of the peak QE and mean QE over 300 nm to 500 nm, respectively. This score indicates the relative position of a spectrum within the measured population and does not represent the percentage of QE lost through aging.

The final review-priority score was

$$S_{\text{priority}} = S_{\text{shape}} + 0.40S_{\text{low}}. \quad (6.11)$$

The low-QE term therefore increased the inspection priority of spectra with unusually low response without allowing QE level alone to determine the quality classification.

Automated quality tiers were assigned from the percentile rank P_{shape} of the shape-anomaly score. Spectra with no kink or physical-range flag were classified as GOLD for $P_{\text{shape}} < 0.25$, SILVER for $0.25 \leq P_{\text{shape}} < 0.45$, and BRONZE for $0.45 \leq P_{\text{shape}} < 0.70$. Spectra with $P_{\text{shape}} \geq 0.70$, or with a kink or physical-range flag, were assigned to REVIEW. The automated classification was then examined together with the measured spectra and the relevant experimental diagnostics.

6.5.1 Automated Anomaly-Screen Output

TM0007 was processed together with the 124 extracted ANTARES PMTs so that all 125 spectra underwent the same automated analysis. It was excluded from the extracted-PMT counts after processing.

The automated pipeline assigned each spectrum to one of four ranking tiers: GOLD, SILVER, BRONZE, or REVIEW. These tiers represent increasing statistical deviation from the central population and are not physical PMT acceptance or rejection categories.

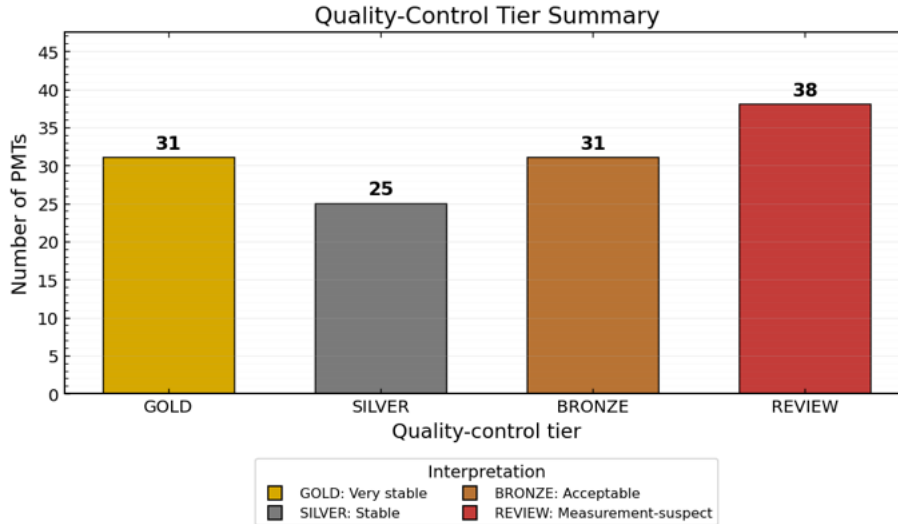


Figure 6.8: Automated quality-control tier distribution for the 125 processed spectra, comprising 124 extracted ANTARES PMTs and the independently measured PMT TM0007. The tiers report the statistical anomaly ranking before manual inspection.

For all 125 processed spectra, the automated output contained 31 GOLD, 25 SILVER, 31 BRONZE, and 38 REVIEW spectra. Because TM0007 was assigned to the BRONZE tier, the extracted-PMT population contained 31 GOLD, 25 SILVER, 30 BRONZE, and 38 REVIEW spectra. The automatically retained extracted-PMT subset therefore contained 86 spectra.

Table 6.1: Automated quality-control output for all 125 processed spectra. The 87 non-REVIEW spectra include TM0007; after excluding TM0007, the extracted-PMT non-REVIEW subset contains 86 spectra.

Automated tier	Number of spectra	Ranking criterion
GOLD	31	Small deviation from the population shape
SILVER	25	Moderate spectral deviation
BRONZE	31	Larger deviation retained by the automated screen
REVIEW	38	Statistical outlier selected for manual inspection
Total	125	124 extracted PMTs and TM0007

Figure 6.9 compares the shape-anomaly and low-QE scores. Increasing horizontal position corresponds to a larger spectral-shape deviation, while increasing vertical position corresponds to a lower QE relative to the population.

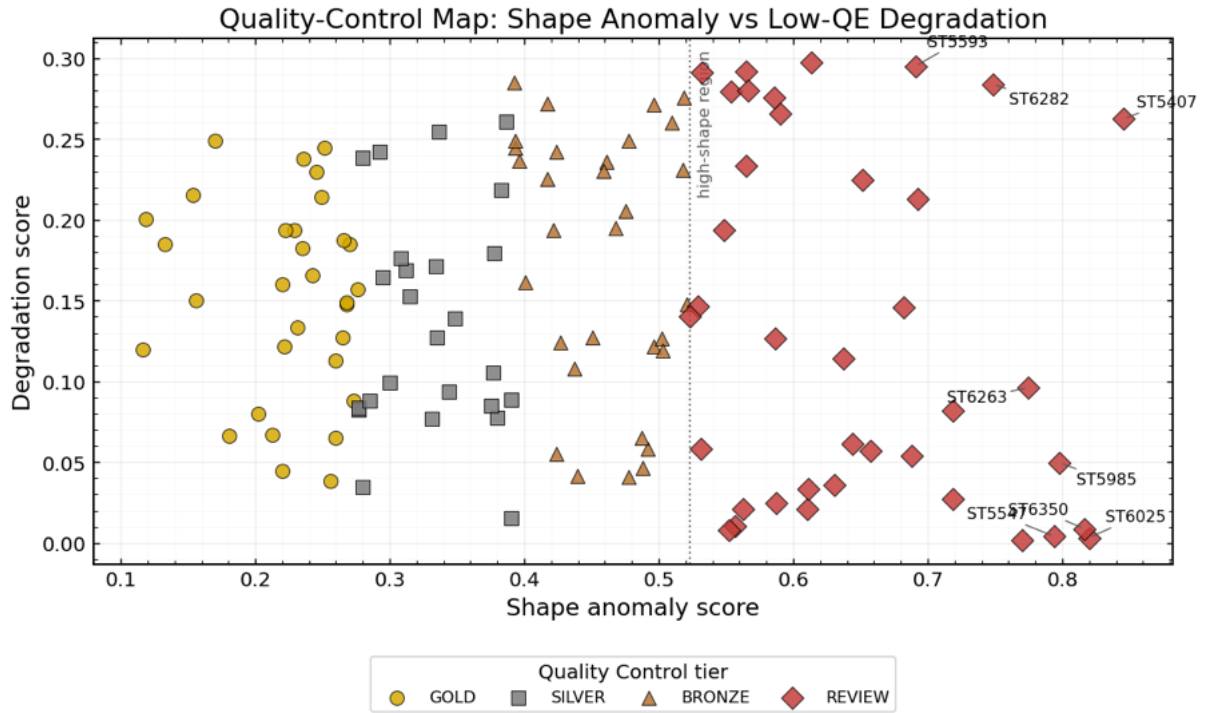


Figure 6.9: Shape-anomaly score plotted against the relative low-QE score. Spectra assigned to the automated REVIEW region were selected for manual inspection. The final measurement disposition was based on the complete spectrum and the available acquisition diagnostics rather than on the score alone.

The 38 REVIEW spectra contained different types of deviations. Some showed unstable dark-current subtraction, photon-flux dependence, or broadband discontinuities. Others retained a smooth wavelength dependence but lay outside the central QE bands. Each REVIEW spectrum was therefore assessed individually before a final measurement disposition was assigned.

6.5.2 Manual Review and Measurement Disposition

I inspected the complete wavelength dependence of the 38 extracted-PMT spectra assigned to REVIEW. The assessment also included dark-current behaviour, measurements at different photon-flux settings, repeated scans where available, and identified instrumental effects.

A spectral deviation was classified as significant when at least one of the following conditions was met:

- the deviation extended over a contiguous wavelength interval and changed the broadband response;
- the feature was reproduced in repeated measurements;
- the spectral response changed systematically with photon flux or acquisition settings;
- the measurement contained an unstable dark-current baseline or another identified instrumental disturbance.

An isolated wavelength point near the 400 nm monochromator transition was retained when the remainder of the spectrum was smooth. Spectra outside the central QE interval were also retained when their wavelength dependence and acquisition conditions were consistent.

Figure 6.10 shows the 38 spectra selected for manual inspection.

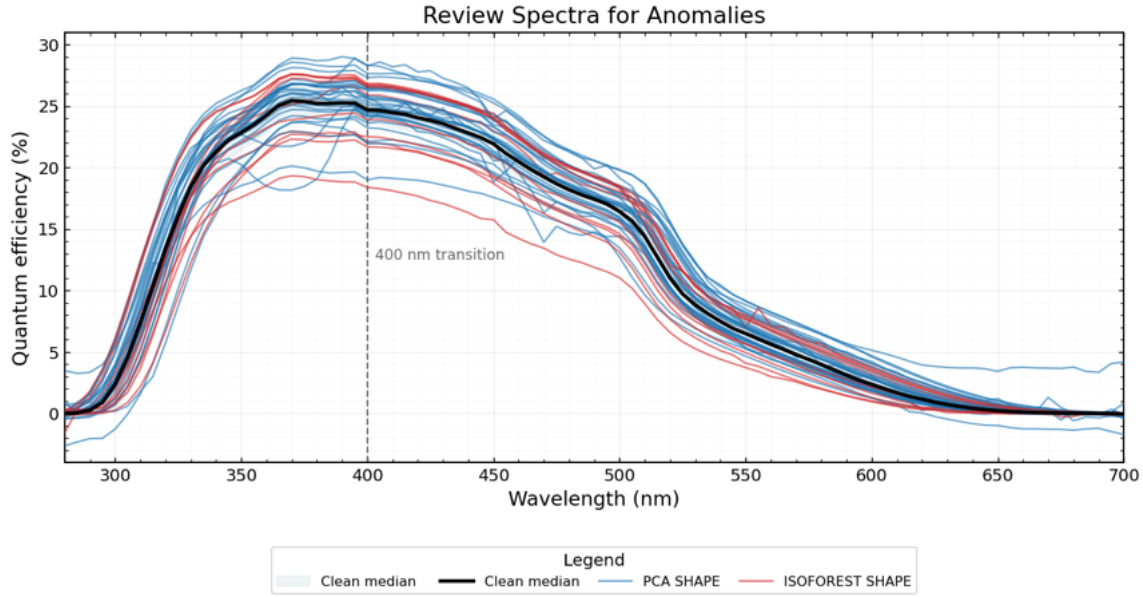


Figure 6.10: The 38 extracted-PMT spectra assigned to the automated REVIEW category. The set contains smooth QE outliers, physically reduced spectra, and measurements affected by spectral or acquisition-related distortions.

The 124 extracted-PMT measurements were assigned to three mutually exclusive measurement dispositions. The low peak-QE flag was recorded separately because it describes the measured QE level rather than the reliability of the measurement.

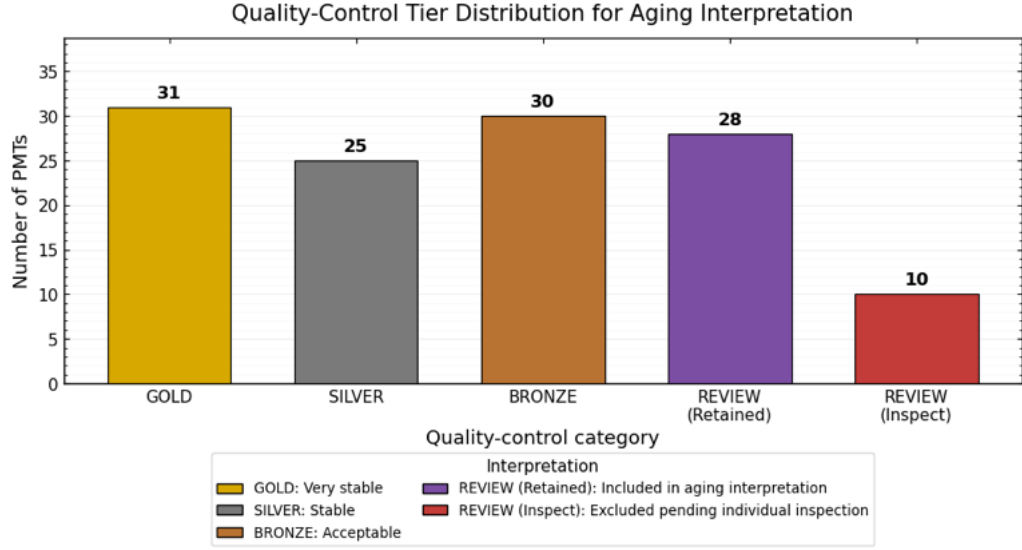
Table 6.2: Final measurement disposition of the 124 extracted-PMT QE measurements. The first three rows are mutually exclusive and sum to the complete extracted-PMT sample. The peak-QE flag is non-exclusive and may overlap with any measurement disposition.

Disposition	Number	Applied criterion
Automatically retained	86	Extracted-PMT spectrum assigned to GOLD, SILVER, or BRONZE by the automated anomaly screen.
Accepted after manual review with measurement caveat	28	REVIEW spectrum with physically interpretable broadband behaviour and either a localized feature, a recoverable acquisition effect, or a QE level outside the central population interval.
Remeasure or focused inspection	10	The present measurement remains unresolved because of unstable dark-current subtraction, photon-flux dependence, saturation-like behaviour, instrumental disturbance, or a strong unexplained contiguous distortion.
Peak QE below 20 %	1	Separate QE-level flag based on the historical ANTARES requirement.

Of the 38 extracted-PMT spectra assigned to REVIEW, 28 were retained after manual inspection. Their wavelength dependence remained physically interpretable, and the automated flag resulted from either a localized deviation, a recoverable acquisition effect, or their position outside the central population bands. The remaining 10 measurements require targeted inspection or remeasurement; the corresponding PMTs are listed individually in Appendix A.5.

Figure 6.11 shows the resulting distribution after excluding TM0007 and separating the original REVIEW category according to the manual assessment. The extracted-PMT population contains

31 GOLD, 25 SILVER, and 30 BRONZE spectra. The original 38 REVIEW spectra are divided into 28 retained measurements and 10 measurements assigned to focused inspection.



The original REVIEW population is divided into 28 retained spectra and 10 spectra assigned to inspect.

Figure 6.11: Quality-control distribution for the 124 extracted ANTARES PMTs after manual inspection of the automated REVIEW category. TM0007 is excluded from these counts. The original REVIEW group is separated into 28 spectra retained for population-level QE interpretation and 10 spectra requiring focused inspection or remeasurement.

The 86 automatically retained spectra and the 28 spectra retained after manual inspection give 114 QE measurements available for population-level spectral interpretation. This number describes the usability of the present QE measurements and is not a detector-reuse fraction.

The PMT with a peak QE below 20% was recorded separately from the measurement-quality categories. A reproducible low-QE spectrum remains a valid physical measurement even when its peak response lies below the historical ANTARES requirement.

Spectra Retained for Population-Level QE Interpretation

The retained population contains 114 extracted-PMT spectra. This set consists of the 86 GOLD, SILVER, or BRONZE spectra retained by the automated screen and the 28 REVIEW spectra retained after manual inspection. The 10 unresolved measurements were excluded because their present spectra contain acquisition-related or broadband features that prevent a secure physical interpretation.

Figure 6.12 shows the complete retained population. The individual spectra follow the expected bialkali wavelength dependence, with the maximum response near 370 nm and a decrease towards longer wavelengths. The principal tube-to-tube variation is the absolute QE level, while the retained-population median remains smooth across the measured wavelength range.

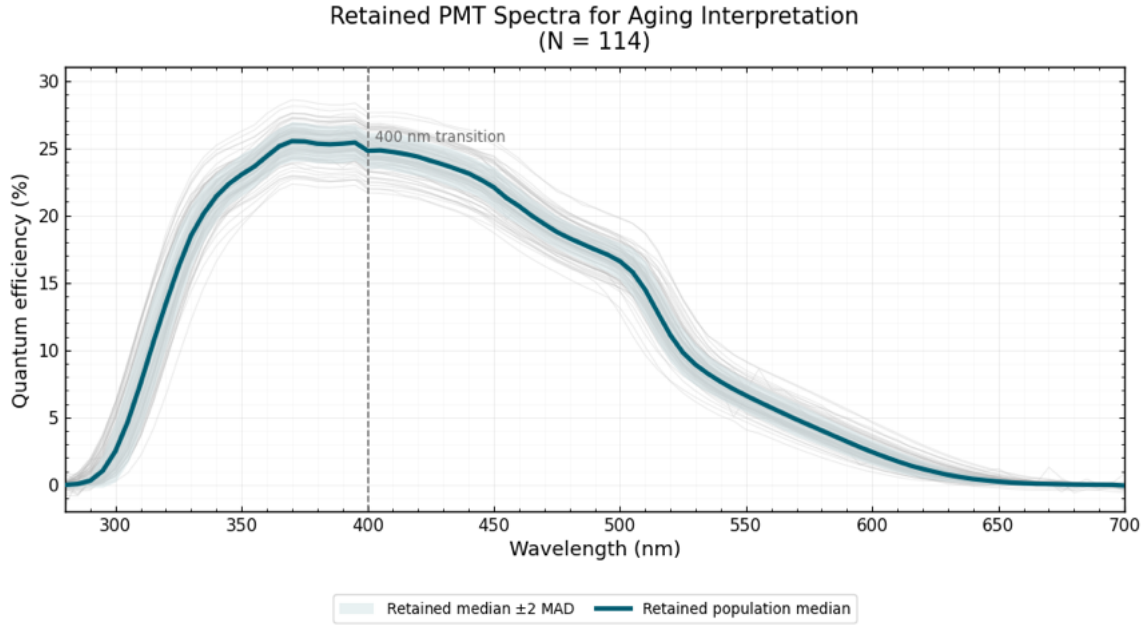


Figure 6.12: The 114 extracted-PMT spectra retained after automated screening and manual review. The grey curves show the individual retained spectra, the dark curve shows the retained-population median, and the shaded region represents the median ± 2 MAD. The vertical dashed line marks the 400 nm monochromator transition.

The retained set is used in Chapter 7 for the post-QC population analysis based on peak QE, mean QE between 300 nm and 500 nm, Cherenkov-weighted QE, and comparison with TM0007 and the historical ANTARES requirement. Including the 28 manually retained spectra prevents statistically unusual but physically interpretable measurements from being removed solely because they lie outside the central automated population bands.

The PMT-level quantities and original automated tier assignments are listed in Appendix A.1. Diagnostic plots for the 38 spectra initially assigned to REVIEW are provided in Appendix A.5.

Chapter 7

Quantum Efficiency and Aging Analysis of Extracted ANTARES Photomultipliers

7.1 Population-Level Quantum-Efficiency Results

The population analysis uses $N = 124$ extracted ANTARES PMTs. For each tube, the wavelength-dependent QE was calculated from the dark-corrected PMT photocurrent and the calibrated photodiode reference measurement described in Chapter 5.

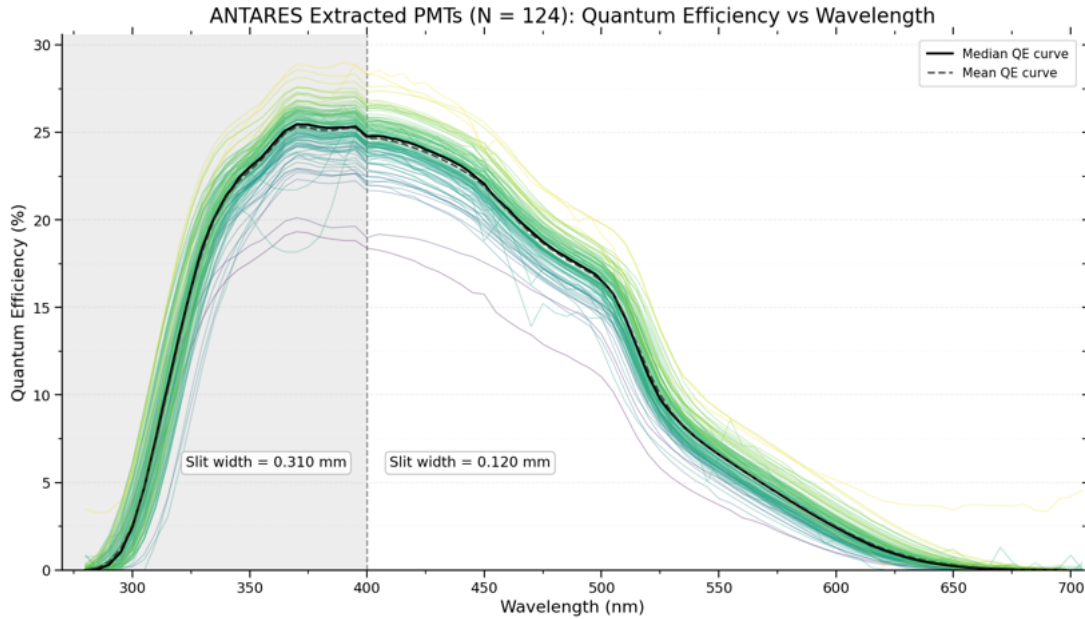


Figure 7.1: Corrected wavelength-dependent QE spectra of the 124 extracted ANTARES PMTs. The solid black curve shows the population median, the dashed black curve shows the population mean, and the vertical dashed line marks the transition between the two slit-width settings used during the spectral scans.

TM0007 is a Hamamatsu R7081-20 photomultiplier tube produced in June 2007. It was not deployed in ANTARES and is treated separately from the extracted-PMT population. The available manufacturer labels of many ANTARES PMTs indicate earlier production dates, commonly in 2001, suggesting that TM0007 originates from a different production batch. In this thesis, the term reference PMT therefore denotes an independent PMT of the same type that provides a common comparison spectrum. It does not represent a calibrated QE standard, an

upper performance limit, or the original pre-deployment response of each extracted PMT.

Figure 7.1 shows the corrected QE spectra of the extracted ANTARES PMT population. The vertical dashed line marks the boundary between the two monochromator slit-width regions. As discussed earlier, wavelengths up to 395 nm were measured with a slit width of 0.310 mm, while wavelengths from 400 nm onward were measured with a slit width of 0.120 mm. The systematic behaviour of this transition was evaluated in Sec. 6.2.2.

Most PMTs follow the same spectral profile. The main tube-to-tube variation is therefore the absolute QE level rather than a change in the general wavelength dependence. The close agreement between the population mean and median also shows that the central population response is not determined by a small number of extreme spectra.

The largest absolute spread occurs near the spectral maximum, where the photocathode response is highest. At wavelengths above approximately 600 nm, the absolute QE and photocurrents are small, making dark-current subtraction and residual measurement fluctuations comparatively more important. The near-ultraviolet and blue region therefore provides the clearest comparison of photocathode sensitivity across the population.

The peak QE of an individual PMT is defined as the maximum value of its measured wavelength-dependent QE spectrum,

$$QE_{\text{peak},i} = \max_{\lambda} [QE_i(\lambda)], \quad (7.1)$$

where $QE_i(\lambda)$ is the measured QE spectrum of PMT i . The peak QE is therefore a property extracted from the complete spectral scan rather than from an independently selected fixed wavelength. For the population median spectrum and the TM0007 reference spectrum, the maximum occurs at approximately 370 nm. This wavelength is consequently representative of the maximum photocathode sensitivity in the measured population.

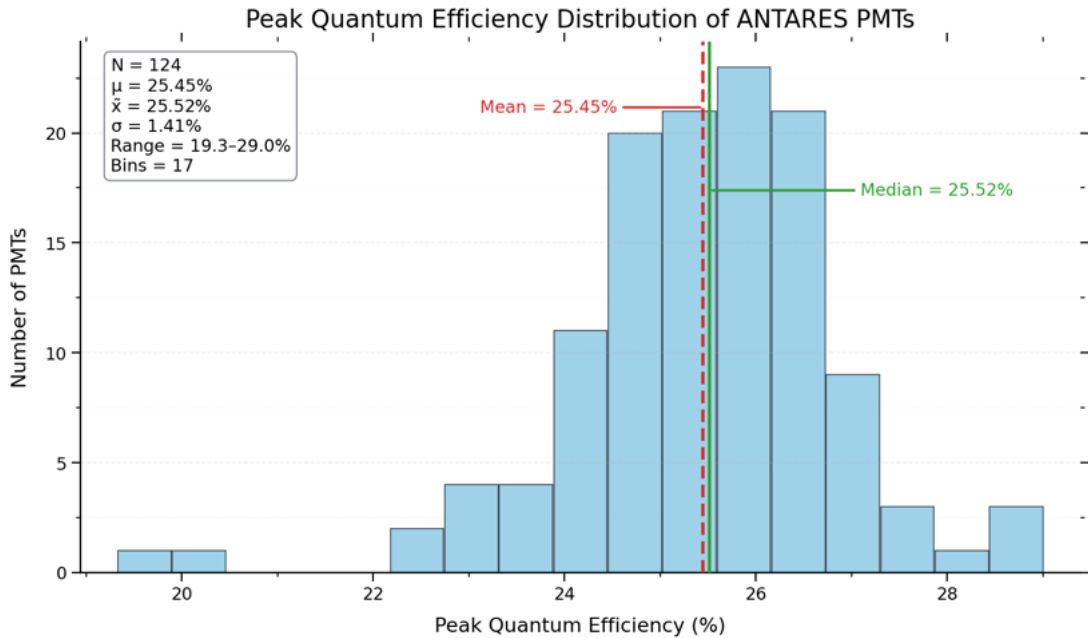


Figure 7.2: Distribution of the individual peak-QE values for the 124 extracted ANTARES PMTs. The vertical lines show the population mean and median.

Figure 7.2 shows a compact and approximately symmetric distribution, with a small lower-QE tail containing only a limited fraction of the measured population.

Table 7.1: Summary statistics of the peak QE for the 124 extracted ANTARES PMTs. The standard deviation is the population standard deviation. TM0007 is listed separately as an independent reference PMT and is not included in the extracted-population statistics.

Statistic	Peak QE
Minimum	19.33 %
16th percentile	24.37 %
Median	25.52 %
Mean	25.45 %
84th percentile	26.50 %
Maximum	29.01 %
Population standard deviation	1.40 percentage points
PMTs below 20 %	1 of 124
TM0007 reference peak QE	24.60 %

Nearly the complete extracted-PMT population exceeds the historical ANTARES peak-QE requirement, while TM0007 lies within the main population range. The reference tube is therefore used as a common comparison spectrum rather than as an upper performance limit.

These full-population results provide the baseline for the wavelength-dependent comparison with TM0007 and the subsequent post-QC aging interpretation.

7.2 Comparison with Reference PMT TM0007

The comparison with TM0007 was used to examine whether the extracted ANTARES PMTs show a systematic reduction relative to an independently measured R7081-20 tube. Figure 7.3 shows the peak-QE values of the extracted PMTs together with the available ANTARES line and optical-module status information.

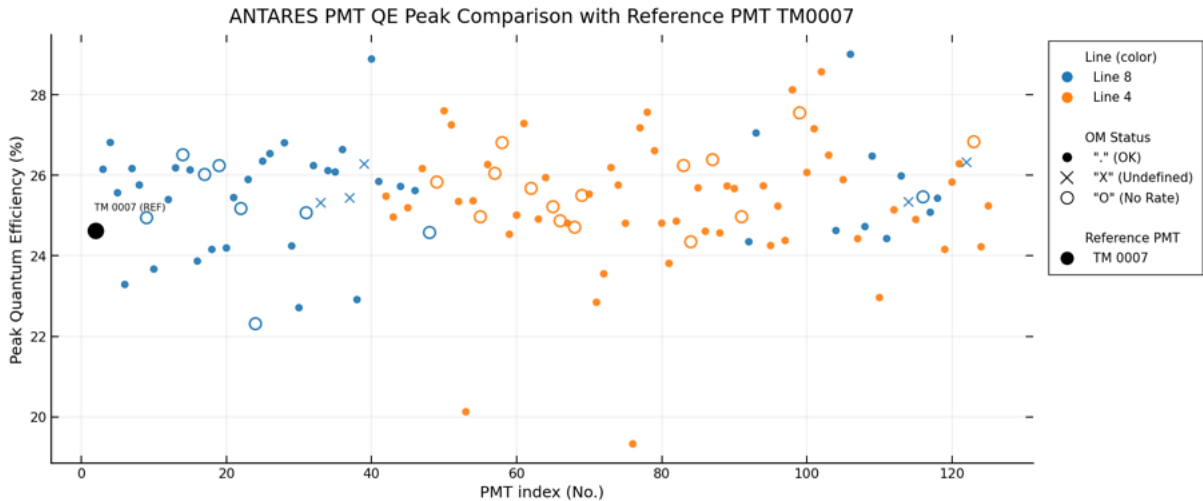


Figure 7.3: Peak-QE values of the extracted ANTARES PMTs compared with TM0007. The colour indicates the ANTARES line, while the marker style indicates the available optical-module status: “.” denotes available nominal rate information, “O” denotes unavailable rate information, and “X” denotes undefined status.

The extracted PMTs from the displayed ANTARES lines occupy largely overlapping peak-QE ranges. No separate low-QE group is associated with either line, and the optical-module status labels do not show a direct correspondence with the laboratory QE values. The observed

spread is therefore dominated by differences between individual PMTs rather than by a simple line-dependent or status-dependent effect.

The population median exceeds the TM0007 peak QE by 0.92 percentage points. This difference is small compared with the full spread of the extracted population, and TM0007 lies within the main population range. The peak comparison therefore provides no evidence for a uniform loss of photocathode sensitivity across the recovered PMTs.

The comparison of the complete spectra is shown in Fig. 7.4.

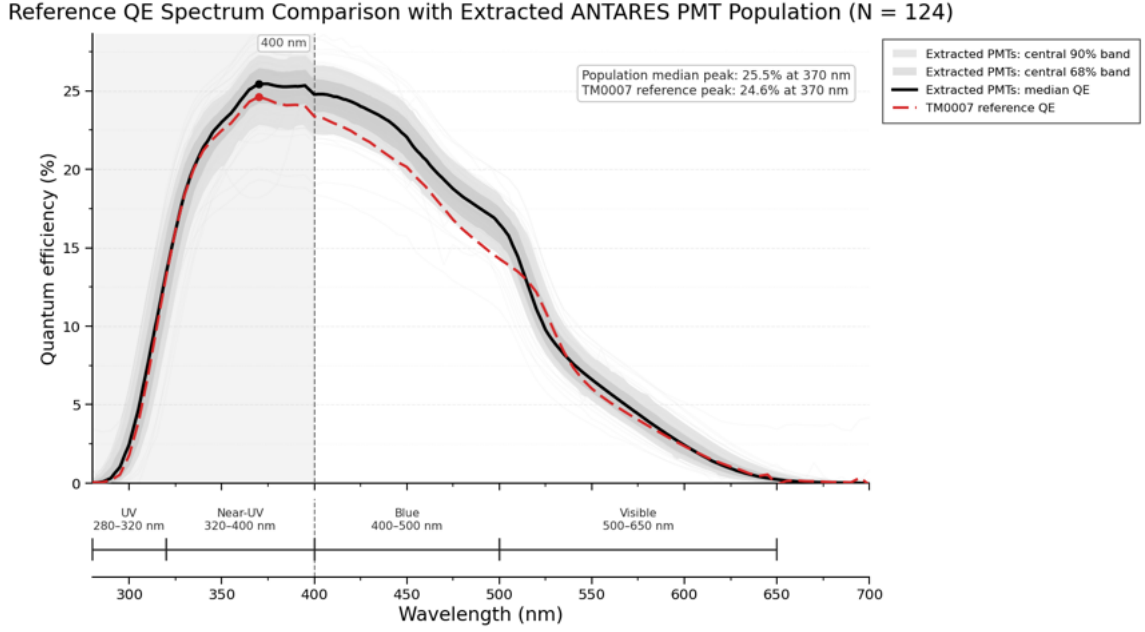


Figure 7.4: Comparison of the corrected TM0007 QE spectrum with the extracted ANTARES PMT population. The black curve shows the population median, the red dashed curve shows TM0007, and the shaded regions show the central population intervals. The main systematic difference appears between approximately 400 nm and 500 nm, where TM0007 lies below the population median.

Below approximately 400 nm, TM0007 and the population median show similar spectral behaviour and reach their maximum at the same wavelength. The more noticeable difference occurs between approximately 400 nm and 500 nm, where the TM0007 QE remains systematically below the population median.

To quantify this difference more directly, the extracted-PMT spectra were compared with TM0007 in absolute QE units. Figure 7.5 shows the wavelength-dependent population difference relative to TM0007 in percentage points, together with band-averaged summaries.

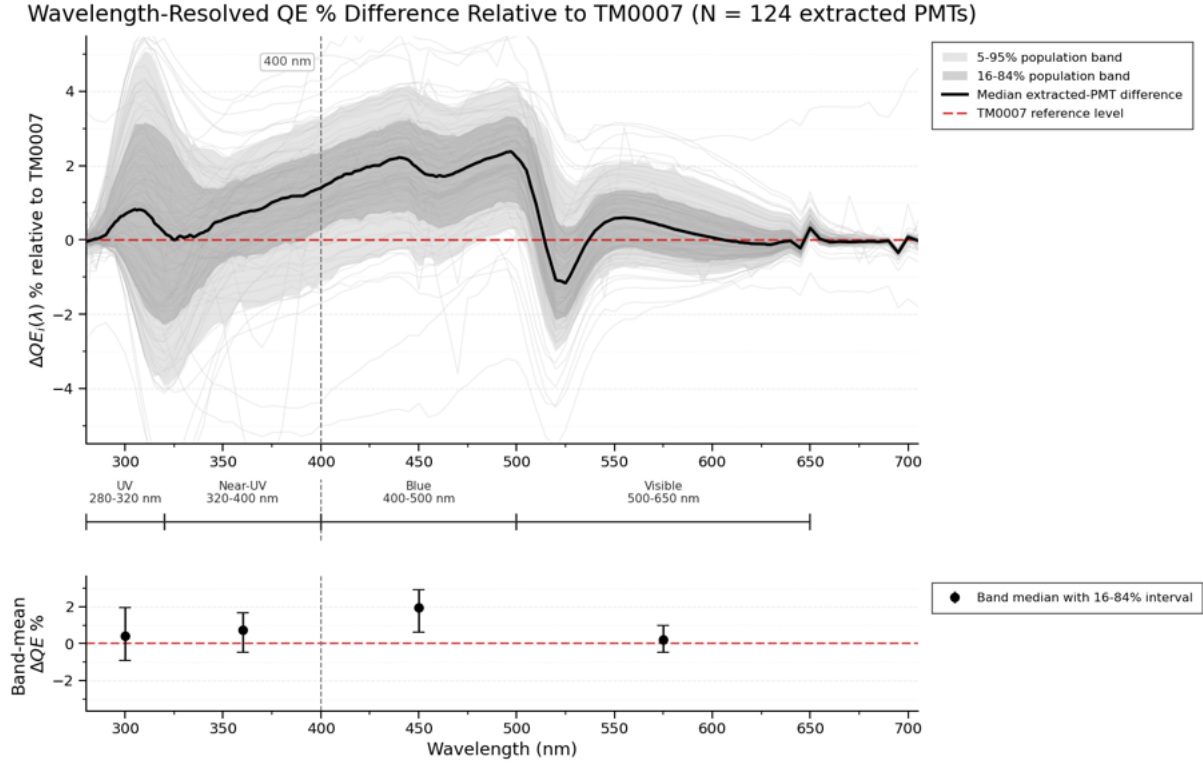


Figure 7.5: Wavelength-resolved comparison of the extracted ANTARES PMTs relative to TM0007 expressed as QE difference in percentage points. The upper panel shows the population median difference and central population bands as a function of wavelength. The lower panel summarizes the same comparison in four wavelength bands. The largest positive offset occurs in the 400 nm to 500 nm blue band.

Table 7.2: Band-resolved QE comparison of the extracted ANTARES PMT population with TM0007. The 16th and 84th percentiles define the central 68% population interval.

Band	Range (nm)	Median ratio	Median ΔQE (pp)	16th percentile ΔQE (pp)	84th percentile ΔQE (pp)
UV	280–320	1.112	0.424	−0.932	1.948
Near-UV	320–400	1.034	0.749	−0.478	1.658
Blue	400–500	1.100	1.945	0.629	2.914
Visible	500–650	1.042	0.221	−0.482	0.981

Table 7.2 shows that the largest difference between TM0007 and the extracted-PMT population occurs in the 400 nm to 500 nm band. In this interval, the complete central population range lies above the TM0007 response. In the other wavelength bands, the central intervals include responses comparable to or below TM0007.

The reduced blue-band response of TM0007 is compatible with tube-to-tube or production-batch variation. Several extracted PMTs show a similarly reduced response in the same wavelength interval, so this feature is not unique to TM0007.

TM0007 is therefore used as an independently measured comparison spectrum, not as a unique pre-deployment baseline. The comparison provides no evidence for a population-wide reduction of QE in the extracted PMTs.

7.3 Post-QC Aging Interpretation and QE-Based Reuse Indicators

The post-QC QE interpretation was restricted to the 114 PMTs retained after the combined automated and manual review. This retained subset contains the 86 automatically retained spectra together with the 28 REVIEW spectra that remained physically plausible after inspection. The 10 follow-up cases were excluded from this interpretation because their present measurements are not sufficiently secure for direct physical assessment.

Since the original pre-deployment wavelength-dependent QE spectrum of each individual PMT is not available, the present analysis does not provide a tube-by-tube before–after aging measurement. Instead, the retained spectra are compared with three reference levels: the historical ANTARES peak-QE requirement of approximately 20 % [12], the independently measured TM0007 reference PMT, and the median QE spectrum of the retained extracted-PMT population.

Figure 7.6 shows the retained extracted-PMT spectra together with the retained-population median, the TM0007 reference spectrum, and a reconstructed 20 % peak-QE requirement curve. The reconstructed requirement curve is scaled to a peak of 20 % and is used only as an approximate historical benchmark rather than as an individual pre-deployment reference.

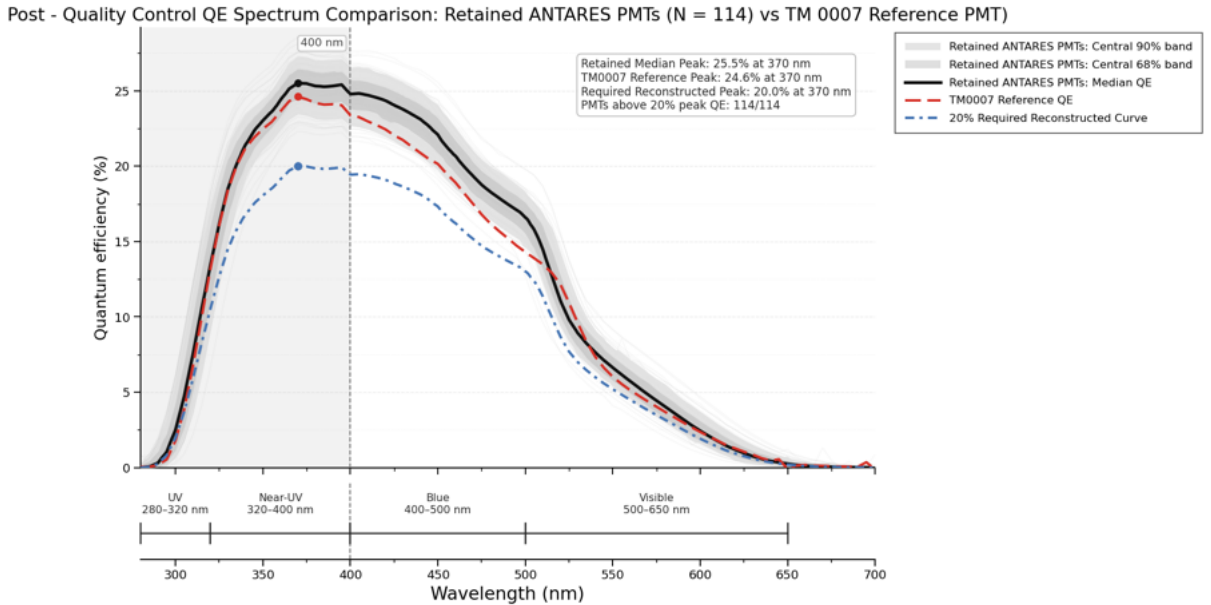


Figure 7.6: Post-QC QE spectrum comparison for the retained extracted ANTARES PMTs ($N = 114$). The black curve shows the retained-population median, the red dashed curve shows the TM0007 reference spectrum, and the blue dash-dotted curve shows the reconstructed 20 % peak-QE requirement curve. The shaded bands indicate the central spread of the retained PMT population.

The retained-population median reaches a peak QE of approximately 25.5 % at 370 nm, while TM0007 reaches approximately 24.6 % at the same wavelength. The reconstructed requirement curve peaks at 20 %. Thus, the retained-population median lies above both TM0007 and the historical requirement in the main sensitivity region. In the retained subset, all 114 PMTs remain above the reconstructed 20 % peak-QE benchmark.

The comparison is also informative away from the peak. Below approximately 400 nm, the retained-population median and TM0007 have similar spectral form and peak at the same wavelength. Between approximately 400 nm and 500 nm, the retained-population median remains systematically above the TM0007 reference, consistent with the earlier reference-PMT comparison. The retained spectra therefore do not indicate a population-wide loss of QE relative to the reference tube in the main Cherenkov-sensitive wavelength range.

To summarize the retained population in scalar form, three QE indicators were used: peak QE, the mean QE over the 300 nm to 500 nm band, and the Cherenkov-weighted QE over the same interval.

The first indicator is the peak quantum efficiency, which gives the maximum photocathode response and can be compared directly with the historical ANTARES requirement.

The second indicator is the mean quantum efficiency in the 300–500 nm band,

$$\overline{QE}_{300-500,i} = \frac{1}{N_\lambda} \sum_{\lambda=300 \text{ nm}}^{500 \text{ nm}} QE_i(\lambda). \quad (7.2)$$

This interval covers the near-UV and blue wavelength region where the PMTs are most relevant for Cherenkov-light detection.

The third indicator is the Cherenkov-weighted quantum efficiency,

$$\langle QE \rangle_{\text{Ch},i} = \frac{\int_{\lambda_1}^{\lambda_2} QE_i(\lambda) \lambda^{-2} d\lambda}{\int_{\lambda_1}^{\lambda_2} \lambda^{-2} d\lambda}, \quad (7.3)$$

with $\lambda_1 = 300 \text{ nm}$ and $\lambda_2 = 500 \text{ nm}$. This scalar metric gives greater weight to the shorter wavelengths, following the dominant $1/\lambda^2$ dependence of the Cherenkov photon yield.

Figure 7.7 summarizes these three scalar indicators for the retained PMTs.

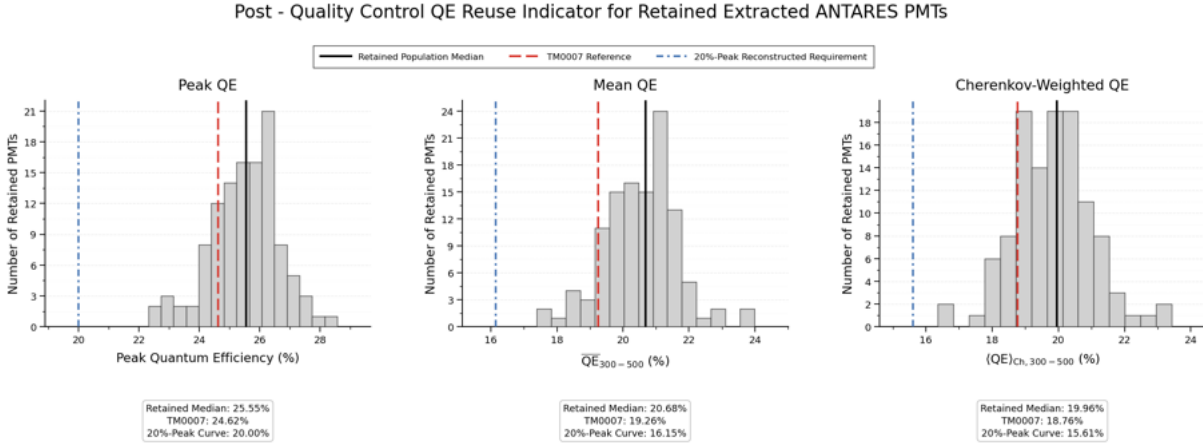


Figure 7.7: Distributions of the three QE indicators for the retained extracted ANTARES PMTs ($N = 114$). The left panel shows peak QE, the middle panel shows the mean QE in the 300–500 nm band, and the right panel shows the Cherenkov-weighted QE over the same interval. Vertical lines mark the retained-population median, the TM0007 reference value, and the reconstructed 20 % peak-equivalent benchmark.

The retained-population median values are approximately 25.55 % for peak QE, 20.68 % for the 300–500 nm mean QE, and 19.96 % for the Cherenkov-weighted QE. The corresponding TM0007 values are approximately 24.62 %, 19.26 %, and 18.76 %. The reconstructed 20 % peak-equivalent benchmark corresponds to approximately 20.00 % in peak QE, 16.15 % in mean QE over 300 nm to 500 nm, and 15.61 % in Cherenkov-weighted QE.

These histograms show that the retained PMT population is concentrated well above the reconstructed requirement level for all three indicators. They also show that the retained-population medians are above the corresponding TM0007 values in each case. The mean-QE and Cherenkov-weighted distributions are shifted to lower absolute values than the peak-QE distribution, as expected, because they average over a wider wavelength interval rather than sampling only the spectral maximum.

The three indicators describe complementary aspects of the retained PMT response. Peak QE captures the maximum response, while the 300–500 nm mean QE and Cherenkov-weighted QE describe the response over the wavelength range most relevant for Cherenkov-light detection. Taken together, these scalar indicators show that the retained PMTs preserve a strong QE response both at the peak and across the main near-UV/blue band.

Finally, the spectral shape of each PMT was compared with the retained-population median. This separates broadband QE reduction from wavelength-localized deviations. The shape-deviation metric used here is the median absolute deviation of the ratio QE_i/QE_{median} over the analysed wavelength range:

$$D_{\text{shape},i} = \text{MAD} \left[\frac{QE_i(\lambda)}{QE_{\text{median}}(\lambda)} \right]. \quad (7.4)$$

Figure 7.8 combines broadband QE level and spectral-shape deviation into a QE-based reuse/degradation map. The horizontal axis shows $\overline{QE}_{300-500}$, while the vertical axis shows the spectral-shape deviation relative to the retained-population median.

Reuse / Degradation Map: Broadband QE Level vs Spectral-Shape Deviation

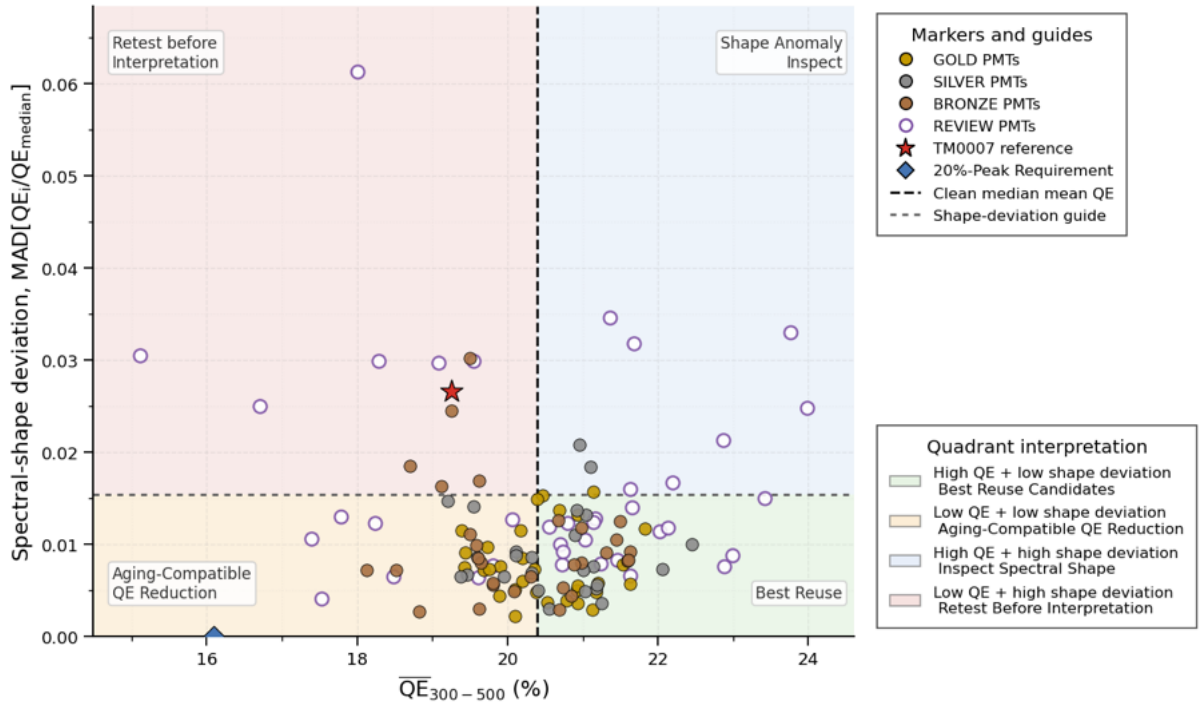


Figure 7.8: QE-based reuse/degradation map based on broadband QE level and spectral-shape deviation. The horizontal axis shows the mean QE in the 300–500 nm band, while the vertical axis shows the spectral-shape deviation relative to the retained-population median. The quadrants separate best QE-based candidates, aging-compatible QE reduction, shape-anomaly inspection cases, and spectra for which the present QE data are not sufficient for a unique physical interpretation.

The lower-right region contains PMTs with high broadband QE and low shape deviation. The lower-left region contains spectra with lower broadband QE but smooth wavelength dependence, consistent with a global QE reduction rather than a localized anomaly. The upper regions contain spectra with larger shape deviation, for which the present QE data alone provide a less secure physical interpretation.

Within the retained subset, the QE-based interpretation is therefore consistent across the spectrum comparison, the scalar reuse indicators, and the degradation map. The retained PMTs remain above the reconstructed historical benchmark, are broadly comparable to or better than

TM0007 in the main sensitivity region, and are concentrated in a relatively compact QE range. From a QE perspective, the retained extracted ANTARES PMTs therefore preserve a strong photocathode response and form the main pool for possible reuse in SWGO.

7.4 Outlier and Case-Study PMTs

The population-level and post-QC aging analysis showed that most extracted ANTARES PMTs retain a stable wavelength-dependent QE response. A small number of spectra, however, were flagged by the quality-control model because they showed unusually low QE, abnormal spectral shape, high dark-current sensitivity, or dependence on measurement conditions.

The PMTs discussed here illustrate different behaviours seen in the extracted population: stable broadband QE reduction, measurement-sensitive low-QE spectra, and wavelength-localized shape distortions. They are useful because they show where the measured QE can be interpreted as a PMT property and where the present measurement is not sufficient for a physical aging claim.

All PMTs in this section were flagged by the QC pipeline. The label is treated as a measurement-level warning, not as a hardware rejection.

Globally Reduced QE Candidate

A first type of outlier is represented by PMTs whose QE spectrum remains smooth and physically plausible, but whose overall response is lower than the central population. In this case, the spectral shape is broadly preserved while the absolute QE level is reduced. This behaviour is more consistent with a broadband loss of photocathode sensitivity than with a localized instrumental artifact.

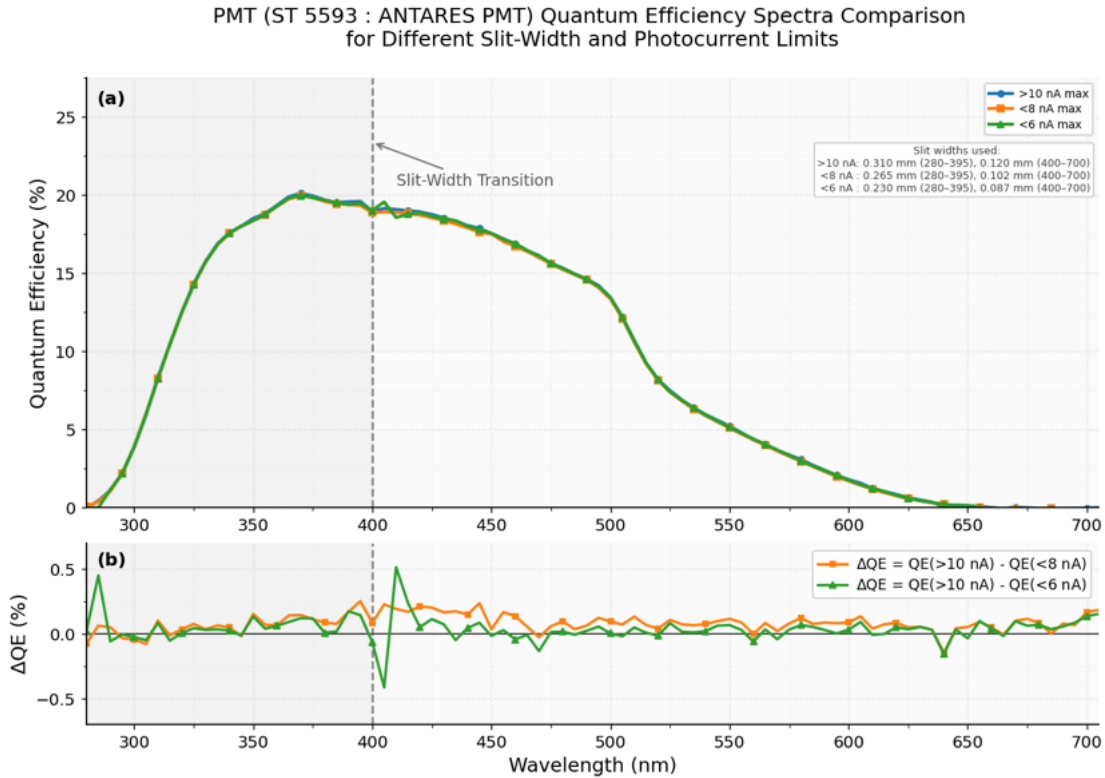


Figure 7.9: QE spectrum comparison for PMT ST5593 under different slit-width and photocurrent-limit settings. The spectra remain nearly unchanged when the photon flux is reduced, indicating that the low-QE response is stable and not strongly dependent on the tested illumination condition.

PMT ST5593 is the clearest stable low-QE case. As shown in Fig. 7.9, repeated measurements under different slit-width and photocurrent-limit settings remain nearly unchanged over the full wavelength range, and the difference curves stay close to zero. The low response is therefore unlikely to be caused by the tested flux setting. Within the limits of this measurement, ST5593 is best interpreted as a globally reduced but stable QE spectrum.

This case shows that a smooth low-QE spectrum should be separated from a distorted or acquisition-dependent spectrum. From a QE perspective, ST5593 may still be relevant for applications with lower sensitivity requirements, but it should be classified separately from the strongest QE-based reuse candidates.

Measurement Suspect Low-QE and Shape-Anomaly Spectra Affected by Dark-Current Instability

Some spectra combine a reduced or distorted reconstructed QE with a dark-current magnitude comparable to, or larger than, the useful photocurrent. A large dark current is not necessarily problematic if it remains stable and can be subtracted accurately. However, when the dark-current baseline changes during the scan, the subtraction defined in Eq. (5.4) no longer represents the detector current accurately at every wavelength.

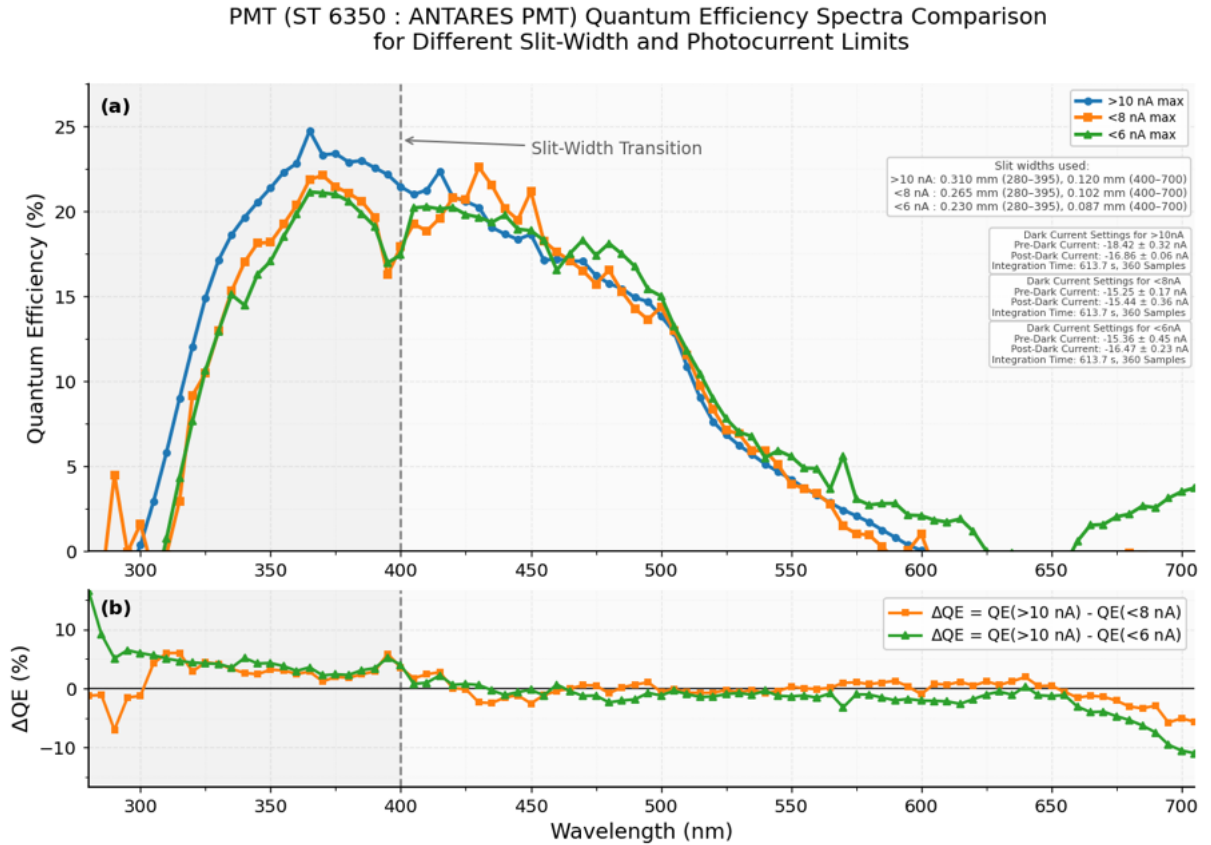


Figure 7.10: QE spectra of PMT ST6350 measured with different slit-width and maximum-photocurrent settings. The dark-current magnitude was approximately 15 nA to 18 nA, exceeding the useful photocurrent, and the pre-scan and post-scan values differed by as much as approximately 1.56 nA. The reconstructed QE is consequently sensitive to the dark-current subtraction, particularly in low-signal wavelength regions.

An error in the estimated dark-current baseline therefore produces the same absolute error in $I_{\text{photo}}(\lambda)$. Its relative effect becomes largest where the optical signal is small, particularly at the ultraviolet and long-wavelength edges of the spectrum.

PMT ST6350 illustrates this problem. Figure 7.10 compares three measurements obtained using different slit widths and maximum-photocurrent settings. The broad spectral response is recognizable in all three scans and remains below the main population over much of the sensitive wavelength range. However, differences between the measurements are accompanied by both a high dark-current magnitude and changes in the baseline during the scans.

For the highest-photocurrent measurement, the dark current changed from (-18.42 ± 0.32) nA before the scan to (-16.86 ± 0.06) nA after the scan. The corresponding baseline change was approximately 1.56 nA. For the measurement limited to below approximately 8 nA, the dark current changed from (-15.25 ± 0.17) nA to (-15.44 ± 0.36) nA. For the measurement limited to below approximately 6 nA, it changed from (-15.36 ± 0.45) nA to (-16.47 ± 0.23) nA, corresponding to a change of approximately 1.11 nA.

The dark-current magnitude was therefore larger than the useful photocurrent in all three measurements. Its variation is sufficient to affect the corrected current, especially at wavelengths where the photocurrent approaches zero. This explains the increasing disagreement between the spectra near the measured wavelength limits and contributes to the differences within the main response region.

The lower broadband response of ST6350 is present in all three measurements, but the present scans do not separate a physical photocathode reduction cleanly from the effect of the changing dark-current baseline. ST6350 should therefore be retained as a possible low-QE candidate with a measurement caveat rather than classified directly as a degraded photocathode. A repeat measurement is required after the source of the elevated dark current has been investigated.

PMT ST6263 represents a more severe case. As shown in Fig. 7.11, the highest-photocurrent scan produces reconstructed QE values far above the physically plausible population range, particularly in the ultraviolet. The disagreement is not explained by photon flux alone. The dark-current magnitude is several times larger than the useful photocurrent and changes substantially between the beginning and end of each scan.

For the highest-photocurrent setting, the dark current changed from (-63.55 ± 0.19) nA to (-43.83 ± 0.13) nA, a change of approximately 19.72 nA. This baseline change alone is larger than the maximum photocurrent targeted during the scan. For the measurement limited to below approximately 8 nA, the dark current changed from (-40.14 ± 0.02) nA to (-35.40 ± 0.03) nA, corresponding to approximately 4.74 nA. For the measurement limited to below approximately 6 nA, it changed from (-28.99 ± 0.12) nA to (-27.73 ± 0.03) nA, corresponding to approximately 1.26 nA.

The expected consequence of this baseline behaviour is visible directly in the spectra. When the assumed dark current differs from the actual baseline during the illuminated scan, the subtraction produces an artificial residual. At short wavelengths, where the corrected spectrum from the highest-current measurement reaches values above 80 %, the reconstructed response is clearly unphysical. The large local maxima and the strong dependence on scan settings must therefore be interpreted as dark-current-subtraction artefacts rather than as photocathode features.

PMT (ST 6263 : ANTARES PMT) Quantum Efficiency Spectra Comparison
for Different Slit-Width and Photocurrent Limits

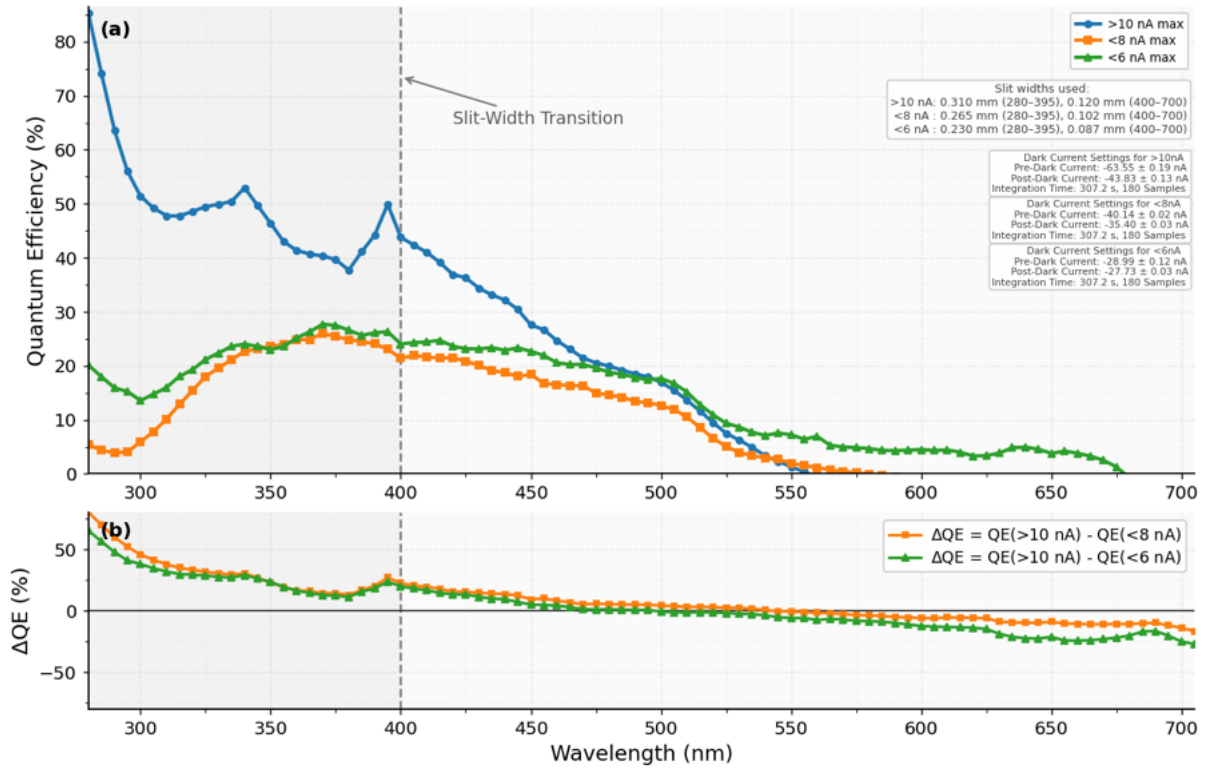


Figure 7.11: QE spectra of PMT ST6263 measured with different slit-width and maximum-photocurrent settings. For the highest-current scan, the dark current changed by approximately 19.72 nA, exceeding the useful photocurrent and producing an unphysical reconstructed response. The reduced-flux scans decrease the distortion but do not remove the underlying dark-current instability.

Repeating ST6263 only at a lower photon flux would not resolve the underlying problem. The elevated and changing dark current may originate from an electrical leakage path in the PMT base, the high-voltage connections, or between dynode stages. The PMT base and cabling should therefore be inspected before another QE scan. If necessary, the voltage-divider stages should be tested sequentially to identify whether a particular dynode connection contributes to the leakage current.

ST6350 and ST6263 demonstrate why both the magnitude and the stability of the dark current must be considered before interpreting an unusual QE spectrum. ST6350 retains a recognizable broadband response but requires confirmation after dark-current diagnosis. The current ST6263 measurements cannot be used for a physical QE assessment until the origin of the unstable leakage current has been identified and corrected.

Recoverable Photocurrent-Dependent Spectral Distortion

PMT ST5407 shows a clear dependence of the reconstructed QE on the maximum photocurrent used during the scan. Three measurements were performed with maximum-current settings above 10 nA, below 8 nA, and below 6 nA, using the corresponding slit widths shown in Fig. 7.12.

The measurement exceeding 10 nA contains two broad depressions that are not reproduced in the reduced-current scans. The first occurs between approximately 345 nm and 395 nm, where the reconstructed QE is lower by as much as approximately 6 percentage points. A second depression appears between approximately 450 nm and 500 nm, with differences reaching approximately 4–5 percentage points. These are contiguous spectral distortions rather than isolated wavelength-point

fluctuations.

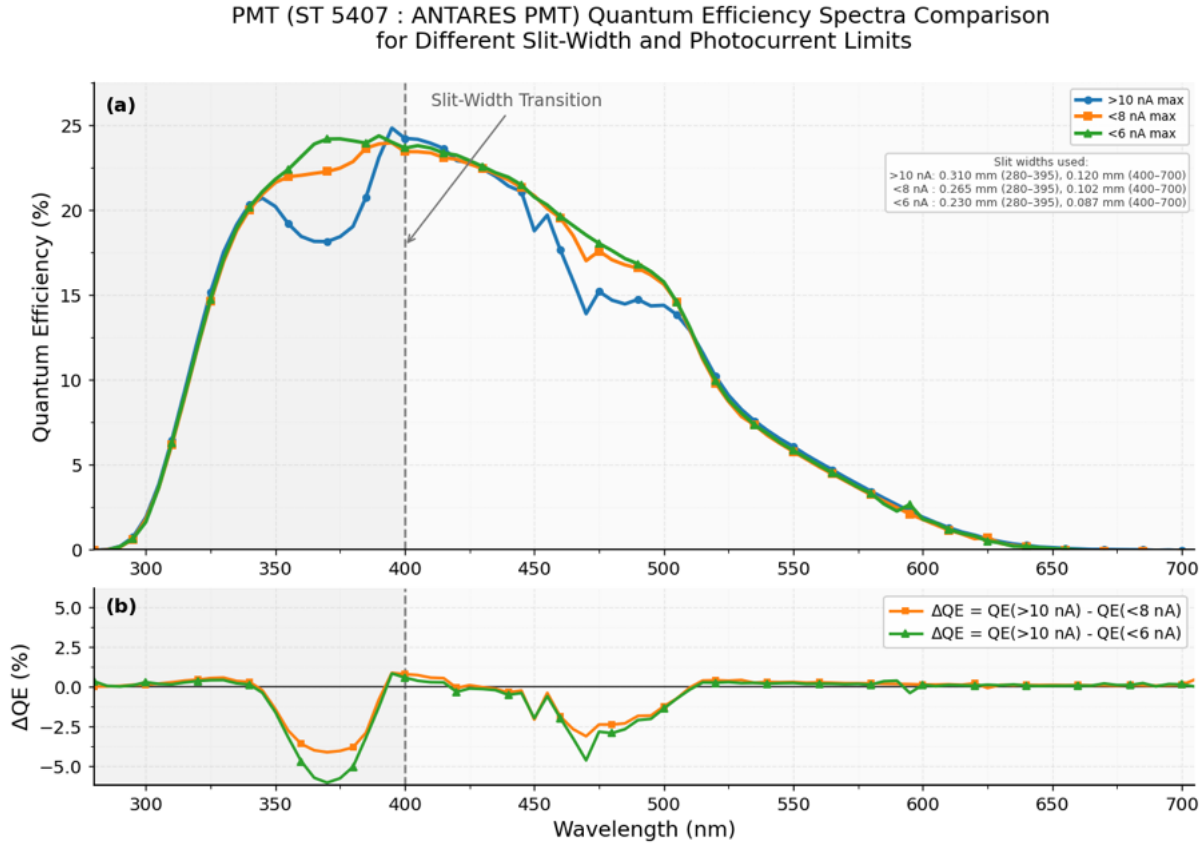


Figure 7.12: QE spectra of PMT ST5407 measured with different slit-width and maximum-photocurrent settings. The scan exceeding 10 nA shows broad QE depressions of up to approximately 6 percentage points in the near-UV region and approximately 4–5 percentage points in the blue region. The measurements limited below 8 nA and 6 nA recover a smooth and mutually consistent spectral response.

By contrast, the scans limited below 8 nA and 6 nA recover the expected smooth bi-alkali spectral response. They show the same broad maximum near 370 nm to 400 nm, similar behaviour through the blue-sensitive region, and the same long-wavelength decrease. The recovery of the spectral shape when the photocurrent is reduced demonstrates that the depressions in the > 10 nA scan are acquisition-dependent and do not represent fixed wavelength-dependent losses in the ST5407 photocathode.

For ST5407, the > 10 nA measurement is therefore outside the usable linear operating range of the present setup. The two reduced-current measurements indicate that the PMT can be measured reliably when the photocurrent is kept below approximately 8 nA. The present measurements bound the onset of the flux-dependent distortion between the < 8 nA and > 10 nA conditions, but they do not determine a more precise saturation threshold because intermediate current levels were not tested.

The result is consistent with a saturation-like or otherwise nonlinear photocurrent response at the highest illumination level. It should be interpreted as a PMT and geometry-specific operating limit rather than as a universal current threshold for all R7081-20 tubes. Most measured PMTs did not show a comparable spectral change at the standard operating current, which indicates that ST5407 has a lower usable photocurrent limit than the main population.

A related current-setting dependence is observed for ST6263: its highest-current scan is strongly distorted, while the reduced-current scans are more physically plausible. ST6263 cannot be used to define the same saturation limit, however, because its dark current is both larger than the

useful photocurrent and strongly time-dependent. ST5407 provides the cleaner example in which reducing the photocurrent alone recovers the expected spectrum.

Interpretation of the Case Studies

The four case studies represent different reasons why spectra from the REVIEW subset could not be accepted for the retained population or the population-level aging analysis. Their main observations and recommended follow-up actions are summarized in Table 7.3.

Table 7.3: Summary of the REVIEW case studies and their present dispositions.

PMT	Main observation	Present disposition
ST5593	Smooth and reproducibly reduced QE response	Confirm with an additional controlled measurement
ST5407	Photocurrent-dependent spectral distortion	Remeasure below approximately 8 nA
ST6350	Reduced response with an elevated and unstable dark-current baseline	Inspect the PMT base and cabling, then repeat the measurement
ST6263	Severe baseline instability producing unphysical QE values	Diagnose high-voltage connections and possible leakage paths before remeasurement

7.5 Line and Storey Dependence

The previous sections treated the extracted ANTARES PMTs mainly as a single measured population. The recovered tubes also have associated metadata from their original detector positions, including ANTARES line number, storey position, and optical-module status. These quantities were used to check whether the measured quantum-efficiency response shows any obvious dependence on the original detector location.

The storey index was used as an approximate detector-location label, not as a precise environmental coordinate. ANTARES was a spatially extended deep-sea detector, with vertical detection lines separated by about 60 m; each standard detection line carried 25 storeys separated by approximately 14.5 m, with each storey holding three optical modules oriented downward at approximately 45° [7, 28].

7.5.1 Line 4 vs Line 8 Comparison

The extracted PMT sample used in this analysis consists of PMTs from ANTARES Line 4 and Line 8. Figure 7.13 compares the peak-region quantum-efficiency distributions for the two lines. Line 4 contains $N = 68$ PMTs, while Line 8 contains $N = 56$ PMTs. The mean values are very similar: $\mu = 25.39\%$ for Line 4 and $\mu = 25.52\%$ for Line 8. The corresponding medians are $\tilde{x} = 25.42\%$ and $\tilde{x} = 25.67\%$, respectively.

The close agreement between the mean and median values indicates that there is no strong line-level separation in the central QE response. Line 4 shows a slightly broader distribution, with a standard deviation of $\sigma = 1.52\%$, compared with $\sigma = 1.27\%$ for Line 8. This larger spread is mainly caused by a small number of lower-QE outliers in Line 4, rather than by a systematic shift of the entire line population.

The full wavelength-dependent spectra for the two lines are shown in Figure 7.14. Both lines exhibit the same general spectral behaviour: the QE rises rapidly in the near-UV region, reaches

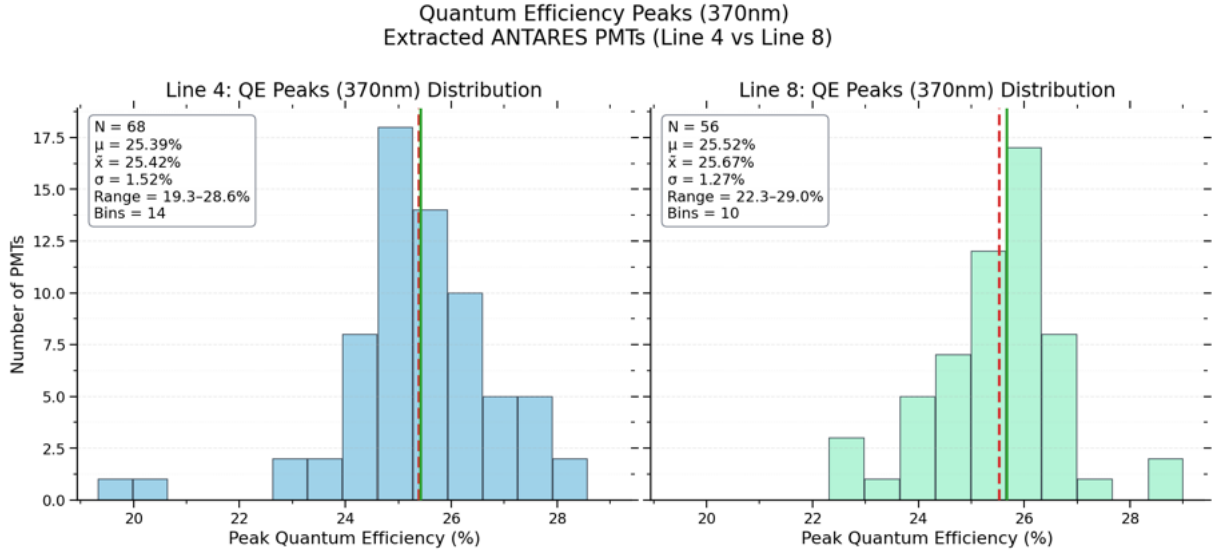


Figure 7.13: Peak-region quantum-efficiency distributions for extracted ANTARES PMTs from Line 4 and Line 8. The red dashed lines indicate the mean values, while the green lines indicate the medians.

its maximum around the blue-sensitive part of the spectrum, and then decreases toward longer wavelengths. The median and mean curves of the two lines are very similar over most of the measured wavelength range.

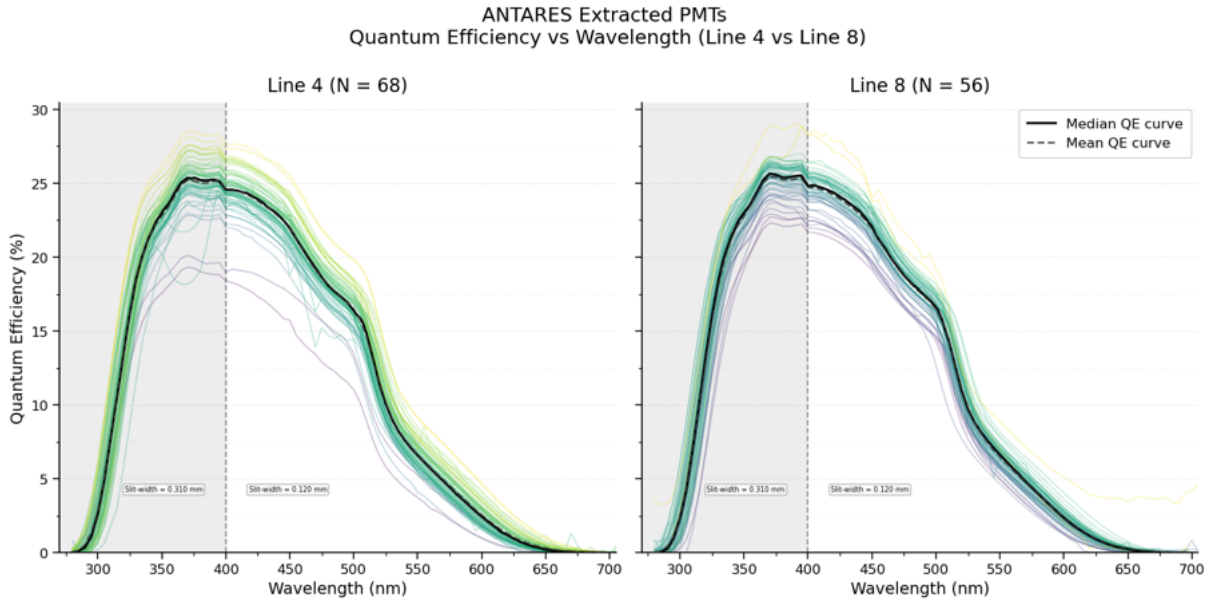


Figure 7.14: Corrected wavelength-dependent QE spectra separated by ANTARES line. The solid black curve shows the line-specific median response, while the dashed black curve shows the corresponding mean response. The vertical dashed line marks the transition between the two slit-width settings used during the spectral scans.

Thus, the present analysis compares the two available ANTARES lines as a consistency check for the measured QE population. Line 4 and Line 8 do not show a clear systematic difference in their typical QE response. The main differences are due to individual PMT outliers and the width of the distribution, rather than a line-wide degradation effect.

7.5.2 Storey-Position Correlation

The storey position provides a vertical-position indicator for the original ANTARES deployment location of each PMT. The analysis was performed to test whether the measured peak QE shows a systematic dependence on detector height, which could indicate a depth-dependent influence from environmental or operating conditions.

In the ANTARES detector geometry, each standard detection line consisted of 25 storeys. The storeys were vertically separated by approximately 14.5 m, and the first storey was located roughly 100 m above the seabed. The detector was deployed at a seabed depth of approximately 2475 m below sea level [7, 28]. If the storey number is denoted by n , with $n = 1$ corresponding to the lowest storey, the height above the seabed can be approximated as

$$h_n = 100 \text{ m} + (n - 1) \times 14.5 \text{ m}. \quad (7.5)$$

The corresponding approximate depth below sea level is

$$d_n = d_{\text{seabed}} - h_n, \quad d_{\text{seabed}} \simeq 2475 \text{ m}. \quad (7.6)$$

For the lowest storey, $n = 1$, this gives

$$h_1 = 100 \text{ m}, \quad d_1 \simeq 2475 \text{ m} - 100 \text{ m} = 2375 \text{ m}. \quad (7.7)$$

For the highest storey, $n = 25$, the height above the seabed is

$$h_{25} = 100 \text{ m} + 24 \times 14.5 \text{ m} = 448 \text{ m}, \quad (7.8)$$

and the approximate depth becomes

$$d_{25} \simeq 2475 \text{ m} - 448 \text{ m} = 2027 \text{ m}. \quad (7.9)$$

The full storey range therefore corresponds to an approximate vertical span of

$$\Delta h = 24 \times 14.5 \text{ m} = 348 \text{ m}. \quad (7.10)$$

The storey index can therefore be used as a depth proxy: lower storey numbers correspond to deeper optical modules, while higher storey numbers correspond to shallower positions. Representative values are summarized in Table 7.4.

Table 7.4: Approximate conversion between ANTARES storey number, height above the seabed, and depth below sea level. The calculation assumes a seabed depth of 2475 m, a first-storey height of 100 m, and a storey spacing of 14.5 m.

Position	Storey n	Height above seabed	Depth below sea level
Lowest	1	100 m	2375 m
Middle	13	274 m	2201 m
Highest	25	448 m	2027 m

The statistical analysis included extracted PMTs for which both a corrected peak-QE value and a valid storey position were available. TM0007 was excluded because it is not part of the extracted ANTARES population. PMTs ST6008, ST5332, and ST5420 were excluded because

their storey positions were unavailable. The final sample therefore contained $N = 121$ PMTs: 68 from Line 4 and 53 from Line 8.

Figure 7.15 shows the peak QE as a function of storey number. The points are separated by ANTARES line and retain the available optical-module status markers. Since increasing storey number corresponds to decreasing deployment depth, a depth-dependent effect would appear as a systematic trend along the horizontal axis.

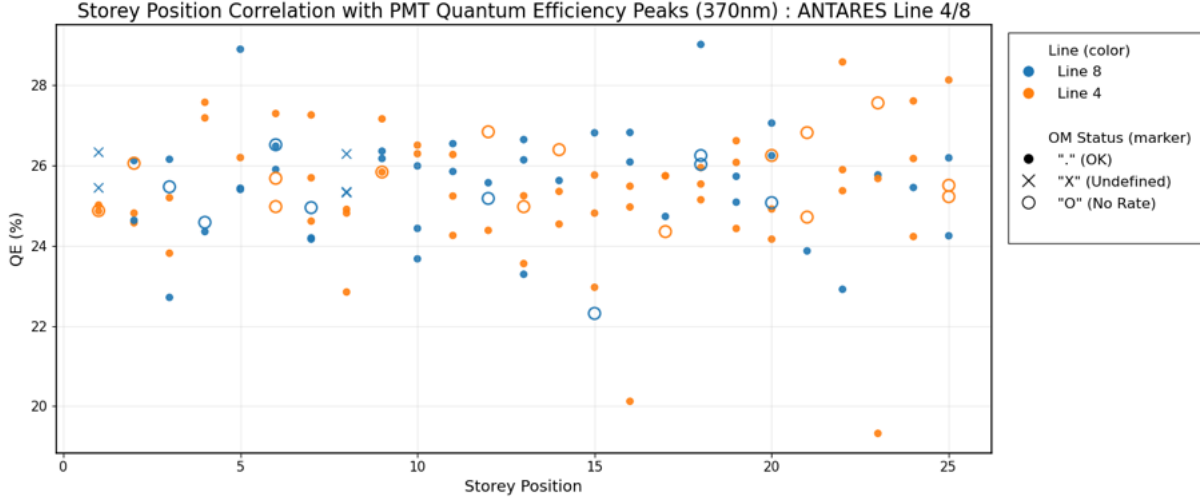


Figure 7.15: Peak QE as a function of ANTARES storey position for the 121 extracted PMTs included in the statistical analysis. The sample contains 68 PMTs from Line 4 and 53 PMTs from Line 8. Lower storey numbers correspond to greater deployment depths, while higher storey numbers correspond to shallower positions.

The relation between storey position and peak QE was tested using Spearman’s rank-correlation coefficient. This non-parametric test was chosen because it identifies monotonic trends without assuming a linear relationship or normally distributed QE values. The test was performed for the complete sample and separately for Line 4 and Line 8 so that a possible line-specific trend would not be hidden in the combined population.

A linear regression was also fitted to quantify the possible change in peak QE per storey. The fitted slope gives the variation in percentage points per storey, while the corresponding 95% confidence interval indicates the range of trends compatible with the data.

Table 7.5: Spearman rank-correlation and linear-regression results for peak QE as a function of ANTARES storey position.

Sample	N	ρ_s	p	Slope (pp/storey)	95% confidence interval (pp/storey)
Combined	121	0.0517	0.574	0.0017 ± 0.0183	$[-0.0345, 0.0379]$
Line 4	68	0.0923	0.454	0.0044 ± 0.0258	$[-0.0472, 0.0560]$
Line 8	53	0.0375	0.790	0.0004 ± 0.0262	$[-0.0521, 0.0529]$

The Spearman coefficients are close to zero for the complete sample and for both lines separately. All corresponding p -values are above 0.05, so the data do not provide evidence for a monotonic association between storey position and peak QE.

The fitted slopes are also consistent with zero because each 95% confidence interval includes zero. For the combined sample, the estimated change is 0.0017 percentage points per storey, with a confidence interval from -0.0345 to 0.0379 percentage points per storey. Separating Line 4 and Line 8 does not reveal a trend that is hidden in the combined population.

PMTs from low, middle, and high storeys occupy comparable peak-QE ranges, while lower-QE

values occur at isolated positions rather than forming a continuous vertical pattern. Within the measured sample, the observed spread is therefore more consistent with individual PMT variation than with a storey-dependent ageing gradient.

The analysis is restricted to two ANTARES lines, and storey number is only a proxy for deployment depth. Nevertheless, neither the rank-correlation test nor the fitted slopes show a statistically supported dependence of peak QE on storey position.

Chapter 8

Angular Quantum Efficiency Response of Extracted ANTARES PMTs

The fixed-geometry QE scans characterize the wavelength-dependent photocathode response near the central illumination position. The angular measurements extend this characterization across the hemispherical photocathode by rotating the PMT while keeping the incident monochromatic beam fixed. In this way, the response is studied as a function of both wavelength and PMT rotation angle,

$$\text{QE}(\lambda) \longrightarrow R_{\text{QE}}(\lambda, \theta), \quad (8.1)$$

where θ denotes the PMT rotation angle used to move the illuminated region across the photocathode. The quantity $R_{\text{QE}}(\lambda, \theta)$ denotes the photocurrent-derived response measured under the controlled angular-scan geometry.

8.1 Motivation for Angular QE Measurements

The Hamamatsu R7081-20 has a large hemispherical entrance window, with the photocathode deposited on the inner curved surface. The photocathode is therefore not flat: its local surface normal changes continuously from the centre towards the edge. When the external beam position is kept fixed and the PMT is rotated, the beam illuminates different regions of this spherical surface and encounters different local incidence geometries.

The measured response can vary across the photocathode for two reasons. First, the local photon-conversion efficiency may not be uniform over the complete photocathode surface. Second, photoelectrons emitted from different positions follow different trajectories through the internal electric field before reaching the first dynode. The measured photocurrent can therefore depend on both the local photocathode sensitivity and the position-dependent collection geometry.

The main purpose of the angular scans was to test the spatial homogeneity of the QE response. Here, spatial homogeneity means that different illuminated regions of the photocathode produce a comparable response under the same wavelength and optical conditions. A central QE measurement alone cannot reveal whether the same response is retained towards the photocathode boundary.

The angular measurements therefore extend the central spectral scan by recording the photocurrent-derived response as a function of wavelength and illuminated photocathode position. They show

whether the spectral shape and absolute response remain stable across the surface, or whether individual regions exhibit reduced or enhanced sensitivity.

This information is relevant for water-Cherenkov detectors because photons can reach different parts of the hemispherical photocathode. A spatially non-uniform response can therefore change the number of photoelectrons produced for the same incident photon flux, depending on where the light reaches the PMT.

During the measurements, the monochromatic beam, iris aperture, light source, monochromator, and current-readout chain remained fixed. Only the PMT was rotated. Changing the rotation angle moved the illuminated point from the photocathode centre towards opposite sides and eventually towards the nominal active boundary. The rotation angle thus provides a controlled laboratory coordinate for measuring the wavelength-dependent spatial homogeneity of the photocathode response.

8.2 Rotation Geometry and Photocathode Coverage

The scan range was chosen to cover the photocathode centre, the transition toward the edge, and a small region beyond the nominal active area where the response was expected to fall.

Figure 8.1 shows the simplified side-view and top-view geometry used to estimate the angular coverage. The side view defines the photocathode curvature and chord length, while the top view indicates the fixed beam direction relative to the rotating PMT body. This estimate only defines the laboratory scan range; it is not a model of the photon-incidence distribution in a water Cherenkov detector.

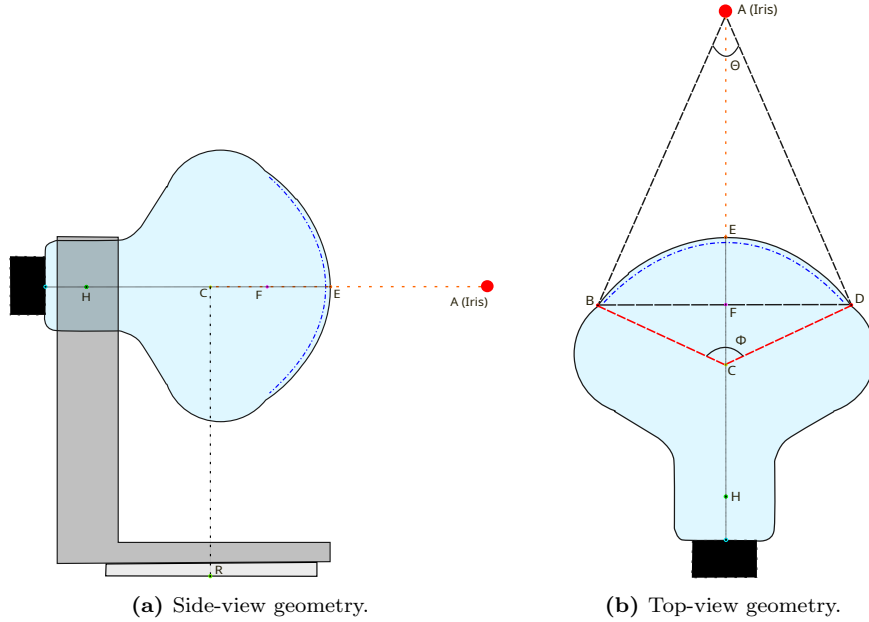


Figure 8.1: Geometry used to estimate the angular range required to scan the PMT photocathode surface.

The photocathode was approximated as a circular arc with radius

$$R = CE = CD = 13.67 \text{ cm}, \quad (8.2)$$

and chord length

$$BD = 22 \text{ cm}. \quad (8.3)$$

Since F is the midpoint of the chord BD , the half-chord length is

$$FD = \frac{BD}{2} = \frac{22 \text{ cm}}{2} = 11 \text{ cm}. \quad (8.4)$$

The half-angle subtended by the photocathode at its centre of curvature follows from the right triangle CFD :

$$\sin\left(\frac{\phi}{2}\right) = \frac{FD}{CD} = \frac{11}{13.67}. \quad (8.5)$$

Therefore,

$$\phi = 2 \sin^{-1}\left(\frac{11}{13.67}\right) \approx 107.2^\circ. \quad (8.6)$$

This gives an approximate symmetric angular coverage of

$$\frac{\phi}{2} \approx 53.6^\circ \quad (8.7)$$

on either side of the central optical axis.

Figure 8.2 illustrates how this angular coverage was implemented experimentally. The iris and beam position remain fixed, while the PMT is rotated through negative, central, and positive angles. At 0° , the beam illuminates the central photocathode region. At positive or negative rotation angles, the beam samples regions displaced toward opposite sides of the photocathode.

The calculated photocathode half-angle of approximately 53.6° motivated extending the nominal scan range to approximately $\pm 60^\circ$. This provided a small margin beyond the estimated photocathode edge. The scan therefore covered the central region, the edge transition, and the response drop outside the main sensitive area.

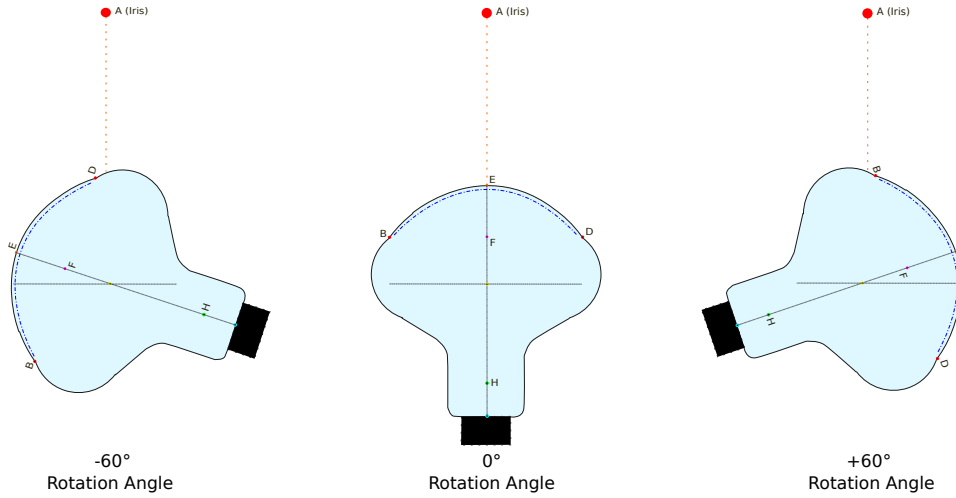


Figure 8.2: Angular QE measurement geometry. The beam position is fixed at the iris, while the PMT is rotated to illuminate different regions of the hemispherical photocathode.

The $\pm 60^\circ$ range should be interpreted as a laboratory scan range chosen to cover the useful photocathode area. In a detector, the photon field depends on the tank geometry, reflection properties, water absorption, and particle direction. Here, the scan isolates how the extracted PMT response changes when different regions of the photocathode are illuminated under controlled laboratory conditions.

The spectral scan procedure described in Chapter 5 was embedded inside a loop over rotation-stage positions. For each requested angle, the shutter was first closed, the rotation stage was

moved to the target position, and the actual angle was read back from the motor controller. The shutter was then opened and a full wavelength scan was performed at that fixed angular position. The final angle sequence was

$$\theta = 0^\circ, 60^\circ, 55^\circ, 50^\circ, \dots, -55^\circ, -60^\circ, 0^\circ. \quad (8.8)$$

The repeated 0° measurements at the beginning and end of the scan were included as internal reproducibility checks. In some angular scans, an additional intermediate 0° spectrum was also recorded.

8.3 Angular Dependence of the QE Spectrum

After defining the rotation geometry and scan sequence, the first step in the angular analysis was to examine how the full wavelength-dependent QE spectrum changes with rotation angle. This check was used to determine whether the angular dependence appears mainly as a broadband change in response, or whether it is dominated by wavelength-localized distortions.

As an internal stability check, the normal-incidence spectrum was measured repeatedly during the angular scan. Figure 8.3 shows the initial, intermediate, and final 0° spectra for PMT ST5567. The three spectra agree closely over the full wavelength range, including the peak region and the long-wavelength fall-off. Slow instrumental drift is therefore unlikely to dominate the angular trend.

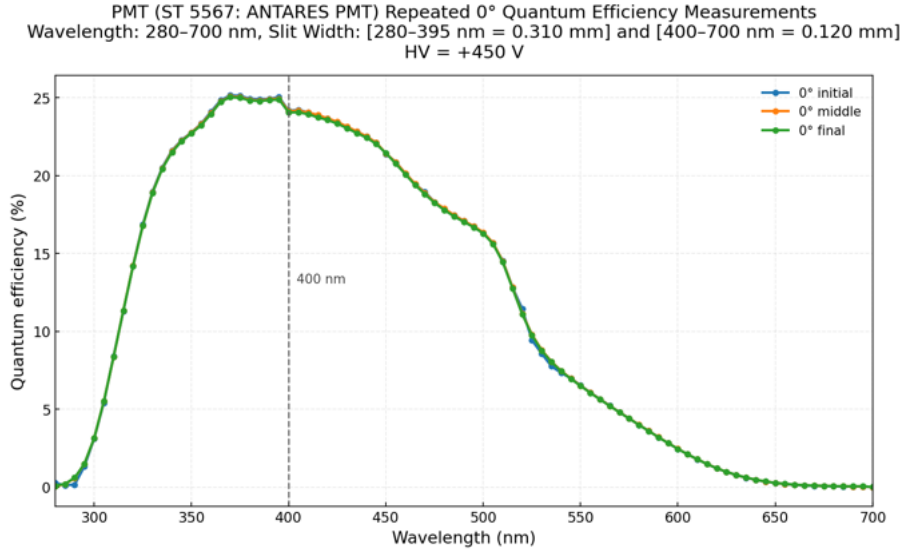


Figure 8.3: Repeated normal-incidence QE spectra for PMT ST5567 measured during the angular scan. The agreement between the initial, intermediate, and final 0° spectra provides an internal stability check for the angular measurement sequence.

Figure 8.4 shows selected QE spectra measured at different rotation angles. The spectra retain the same overall wavelength dependence as the normal-incidence response: the QE rises in the near-UV, reaches its maximum in the blue-sensitive region, and then decreases toward longer wavelengths. Changing the rotation angle mainly changes the absolute QE level, while the spectral shape remains broadly preserved.

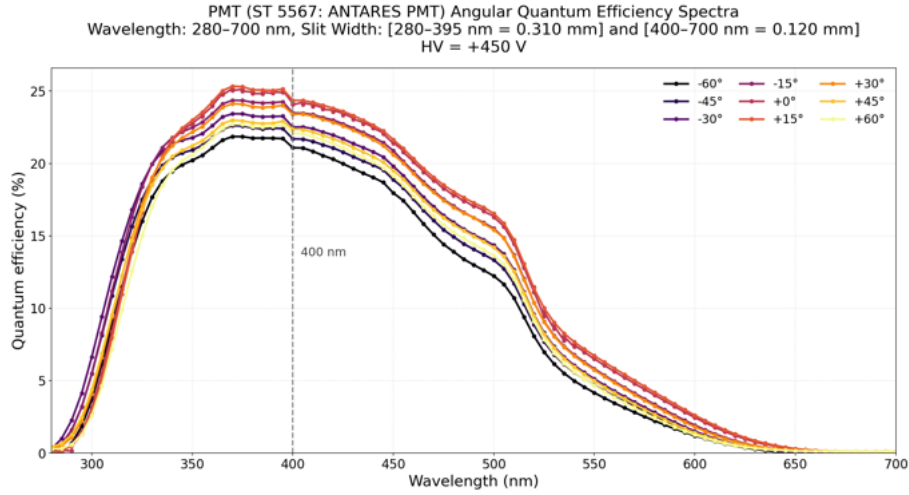


Figure 8.4: Angular QE spectra for PMT ST5567. The general spectral shape is preserved at different rotation angles, while the absolute QE level changes as different regions of the photocathode are illuminated.

The strongest response is observed near the central angular region, where the beam illuminates the central part of the photocathode. At larger positive and negative angles, the response decreases as the illuminated region moves toward the photocathode edge. Because this reduction occurs over a broad wavelength range, it is interpreted mainly as a position-dependent photocathode and collection-geometry effect rather than as a new wavelength-dependent systematic.

The same behaviour is shown more compactly in the two-dimensional QE maps in Fig. 8.5. The full-range map shows the complete measured spectrum, while the zoomed map focuses on the 300–550 nm interval, where the PMT response is highest and most relevant for Cherenkov-light detection. In both views, the high-QE region is concentrated around the central angular range and decreases smoothly toward larger absolute angles. The dashed line marks the 400 nm slit-width transition, previously identified as an instrumental transition region; it does not dominate the angular trend.

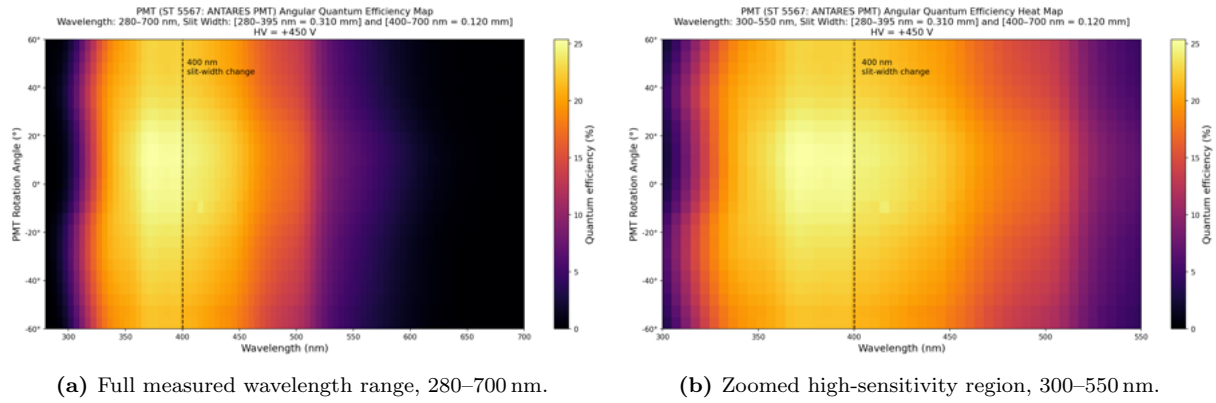


Figure 8.5: Angular QE maps for PMT ST5567. The colour scale represents the measured QE as a function of wavelength and corrected physical incidence angle. The full-range map shows the complete measured spectrum, while the zoomed map highlights the main Cherenkov-sensitive and high-QE region used for the later spatial-response analysis. The dashed vertical line marks the 400 nm slit-width transition.

The three-dimensional surface representation in Fig. 8.6 provides a complementary view of the same angular response. It makes the broad high-QE plateau and the reduction toward larger absolute angles visually explicit. However, the two-dimensional heat maps are used for the main interpretation because they show the wavelength–angle structure more directly and avoid perspective-related ambiguity.

PMT (ST 5567: ANTARES PMT) Angular Quantum Efficiency Surface Map
Wavelength: 280–700 nm, Slit Width: [280–395 nm = 0.310 mm] and [400–700 nm = 0.120 mm]
HV = +450 V

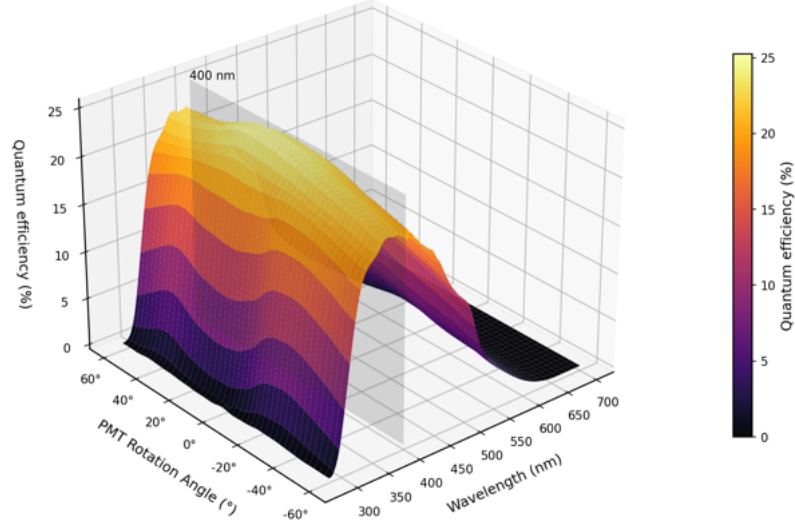


Figure 8.6: Three-dimensional representation of the angular QE response for PMT ST5567. The surface illustrates the broad high-QE region and the reduction in response toward larger absolute angles.

Overall, the angular spectral scans show that the spectral shape remains stable while the absolute response changes with rotation angle. The following angular analysis therefore uses a representative wavelength near the QE maximum. The wavelength 370 nm is used for this purpose because it lies close to the measured peak response and provides a high signal-to-noise point for studying the spatial response across the photocathode.

8.4 Spatial QE Response and Dynode-Orientation Dependence

The rotation angle was converted into a distance from the PMT symmetry axis using the geometrical relation introduced in Section 8.2,

$$d(\theta) = R \sin \theta, \quad (8.9)$$

with $R = 136.7$ mm. In this representation, $d = 0$ corresponds to illumination near the photocathode centre, while positive and negative distances correspond to illumination on opposite sides of the photocathode. The nominal photocathode edge is marked at approximately $|d| = 110$ mm, corresponding to the half-chord estimate used in the angular-range calculation.

8.4.1 Dynode-Orientation Configurations

The spatial response can depend not only on the radial distance from the photocathode centre, but also on the orientation of the internal dynode structure. After a photon releases a photoelectron from the photocathode, the electron must still be guided to the first dynode. This collection step is not necessarily rotationally symmetric, because the internal electrode and dynode geometry introduce preferred directions inside the PMT. Two points at similar distance from the photocathode centre may therefore produce slightly different measured responses if they are located differently with respect to the dynode system.

To test this effect, the angular scans were repeated for two relative PMT orientations. In the first configuration, denoted here as dynode orientation 0° , the dynode structure was aligned with

the scan plane. In the second configuration, denoted as dynode orientation 90° , the PMT was rotated around its symmetry axis before repeating the angular scan. The beam and external optical setup remained unchanged; only the azimuthal orientation of the PMT with respect to the scan plane was changed.

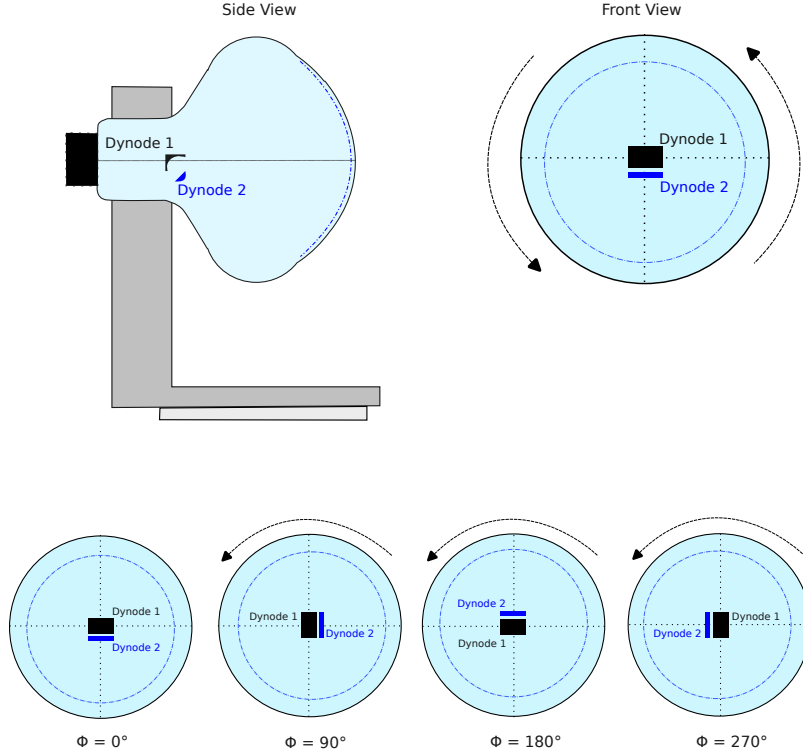


Figure 8.7: Dynode-orientation configurations used for the angular QE comparison. Repeating the angular scan for different PMT orientations allows possible dynode-related asymmetries to be separated from purely radial photocathode-position effects.

This comparison separates radial photocathode-position effects from possible dynode-orientation effects. If both orientations show similar behaviour, the measured response can be described mainly as a function of distance from the PMT symmetry axis. If they differ, the internal collection geometry must also be considered when interpreting the spatial QE response. The following plots therefore compare both the absolute QE behaviour of individual PMTs and the normalized mean response for the two dynode-orientation configurations.

8.4.2 Photomultiplier Spatial Response

Figure 8.8 shows the detailed spatial scan of PMT ST5937 at 370 nm for dynode orientation 0° . The scan was extended to approximately $\pm 80^\circ$ to include both edge transitions and the region outside the main photoresponsive area.

For this PMT, the central QE is approximately 24 % to 25 %. The sharp transitions at larger displacements provide the positions required for estimating the effective photocathode boundary under the applied illumination geometry.

These edge transitions can be used to estimate the effective photocathode size under the applied illumination geometry. The angular scan positions were converted to linear positions along the photocathode surface according to

$$d = R \sin \theta, \quad (8.10)$$

where R is the PMT radius and $d = 0$ corresponds to the centre of the photocathode. If d_L and d_R denote the linear positions on the left and right sides of the scan, respectively, at which the measured response falls below a defined fraction of the central response, the effective photocathode diameter along the scanned direction is

$$D_{\text{eff}} = d_R - d_L. \quad (8.11)$$

Assuming that the active photocathode boundary is approximately circular, the corresponding effective area can be estimated as

$$A_{\text{eff}} \simeq \pi \left(\frac{D_{\text{eff}}}{2} \right)^2. \quad (8.12)$$

For a single angular scan, this area estimate relies on rotational symmetry because the measurement directly determines only one effective chord across the photocathode. Measurements along additional PMT orientations provide a check of this assumption and allow possible directional differences in the active boundary to be identified.

Small local increases are visible immediately before the final response drop. These points were not used to define an enhanced photocathode response because they occur in the boundary region, where partial beam overlap, finite beam size, window curvature, reflections, and alignment sensitivity can affect the measured current. The effective edge should therefore be obtained from a consistent response criterion applied to the falling part of the curve rather than from an individual local maximum.

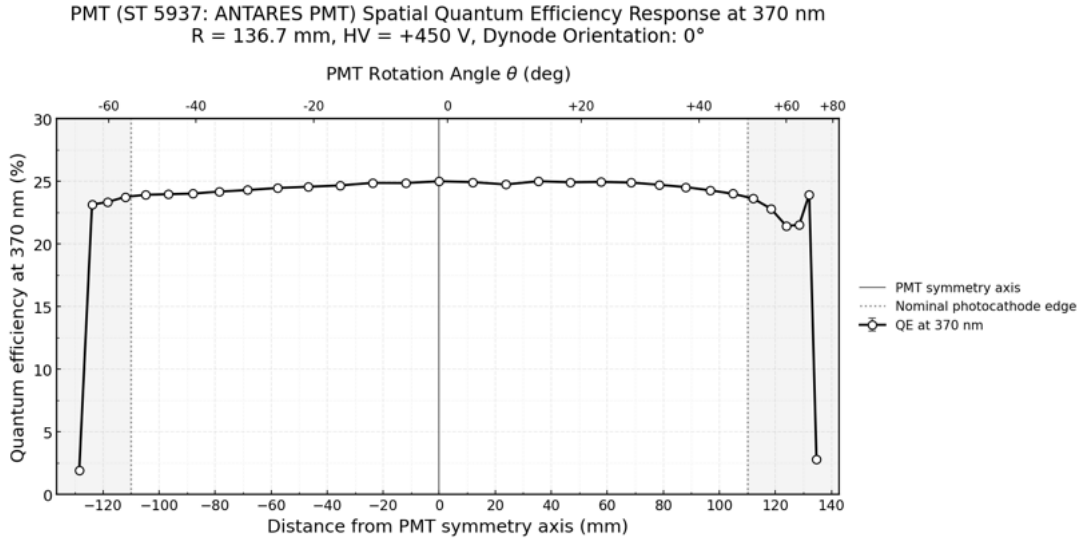


Figure 8.8: Spatial QE response of PMT ST5937 at 370 nm for dynode orientation 0°. The vertical solid line marks the PMT symmetry axis, while the dotted lines indicate the nominal photocathode edge. The scan was extended beyond the nominal edge to diagnose where the photoresponse drops outside the active photocathode region.

The single-PMT scan was then extended to a small PMT sample. Figure 8.9 shows the spatial QE response at 370 nm for several PMTs measured with dynode orientation 0°. The PMTs show similar central behaviour: the response remains broadly stable across most of the photocathode, with PMT-to-PMT differences mainly appearing as offsets in absolute QE level.

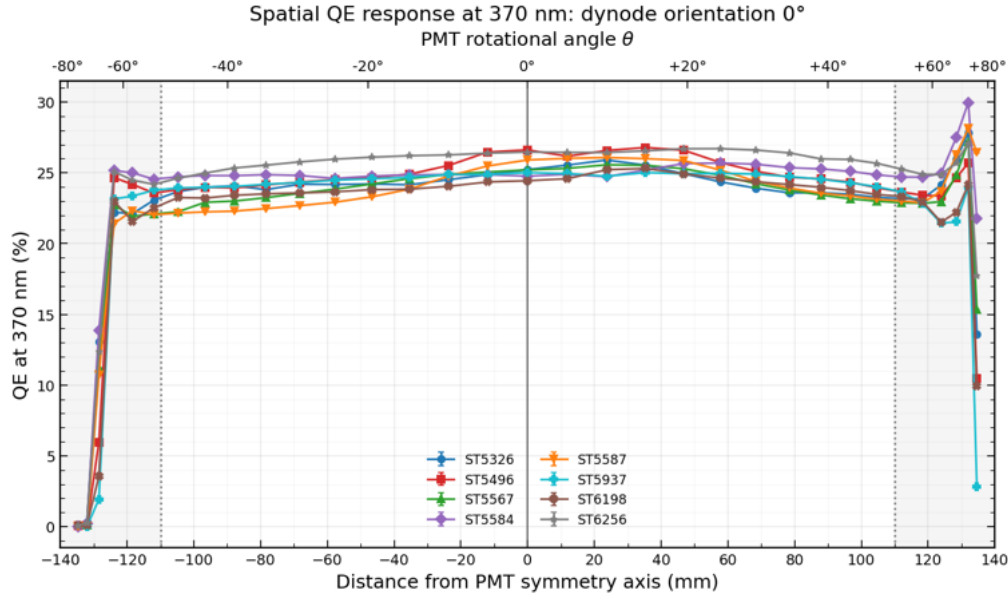


Figure 8.9: Spatial QE response at 370 nm for several PMTs measured with dynode orientation 0° . The central region shows a broad and stable response plateau, while the response decreases near and beyond the nominal photocathode edge.

A corresponding set of measurements for dynode orientation 90° is shown in Fig. 8.10. The same overall structure is observed: a broad central plateau followed by a strong reduction near the photocathode edge. The absolute QE values differ between PMTs, but the spatial pattern remains similar. This behaviour is consistent with a common photocathode-geometry response rather than a feature unique to one tube or one dynode orientation.

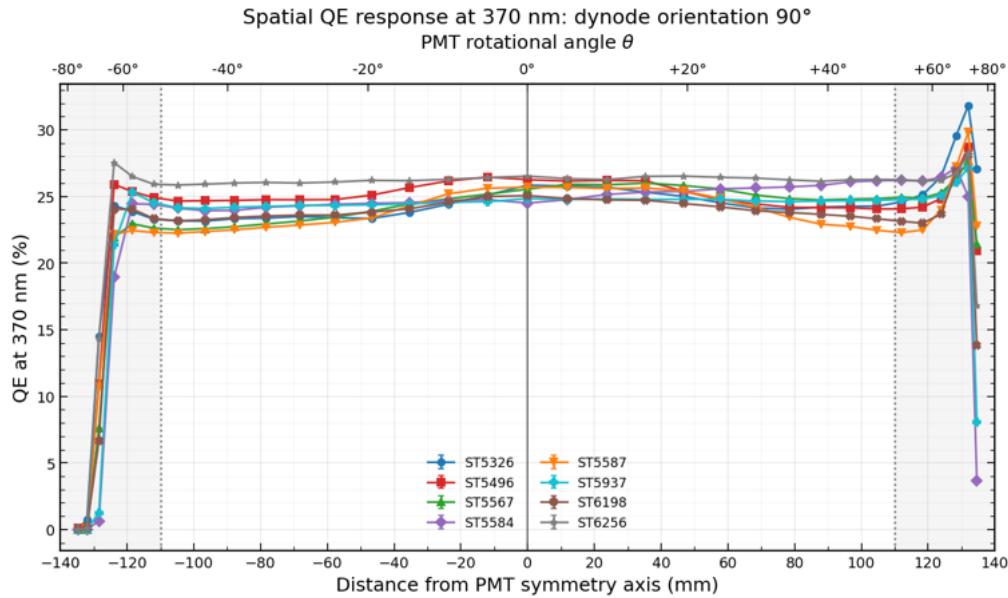


Figure 8.10: Spatial QE response at 370 nm for several PMTs measured with dynode orientation 90° . The measured PMTs again show a stable central response region and a strong decrease near the photocathode edge.

The central photocathode response is similar for the two dynode-orientation groups. Larger differences appear only near the nominal photocathode boundary at approximately $|d| = 110$ mm, where the measured response changes rapidly with position.

On the positive-distance side, both datasets show a local increase immediately before the final

response drop. This feature is reproduced across several PMTs and is therefore not consistent with a single fluctuating measurement point. However, it should not be interpreted directly as an intrinsic increase in the local photocathode QE. Near the edge, the beam intersects the strongly curved window at an oblique angle. The projected beam footprint becomes elongated, and a small change in rotation angle produces a comparatively large change in the overlap between the beam and the active photocathode. Internal reflections at the glass boundary may additionally redirect part of the incident light onto the sensitive surface.

The measured photocurrent near the boundary can also depend on the collection of photoelectrons emitted from that region. Electrons produced close to the photocathode edge follow different trajectories towards the first dynode than electrons emitted near the centre. A local increase can therefore arise from the combined optical geometry and position-dependent collection efficiency, rather than from a higher photon-conversion probability alone. The dynode-orientation measurements discussed later test this interpretation by examining whether the edge feature changes when the PMT is rotated around its symmetry axis.

The absence of an equally strong peak at the opposite edge shows that the response is not perfectly symmetric about the nominal mechanical centre. This asymmetry may result from a small displacement between the beam axis, rotation axis, and true photocathode centre, together with a direction-dependent electron-collection response. It motivates the angular zero-offset correction introduced in Sec. 8.4.3.

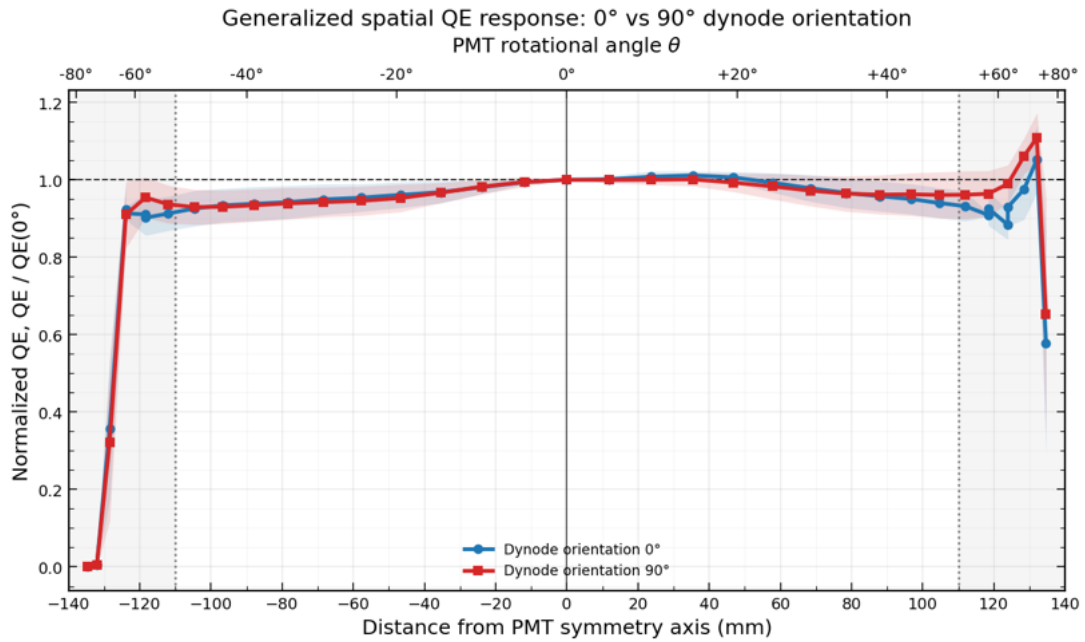


Figure 8.11: Mean normalized spatial response at 370 nm for dynode orientations 0° and 90° . Each curve is normalized to its value at $d = 0$, and the shaded regions show the PMT-to-PMT spread.

After normalization to the response at $d = 0$, the two orientation groups remain close to the central value over most of the nominal photocathode diameter and change rapidly only near the boundary. This broad central plateau followed by an edge-region decrease is the general spatial-response pattern observed in the measured sample.

The main differences between the normalized orientation groups are localized near the edge, particularly in the amplitude of the positive-distance enhancement and the position of the final response transition. The displaced and asymmetric edge structure motivates the angular zero-offset correction introduced in Sec. 8.4.3.

8.4.3 Angular Zero-Offset Correction

The measured edge transitions are displaced towards positive distance relative to the nominal mechanical zero angle. This indicates that the nominal 0° stage position did not coincide exactly with the symmetry axis of the illuminated photocathode response.

The offset is interpreted as a physical alignment offset of the measurement setup, not as an intrinsic PMT effect. Possible contributions include a small displacement between the beam axis and the PMT centre, mechanical mounting tolerances, finite beam size at the photocathode, and a rotation axis that does not pass exactly through the geometrical centre of the hemispherical photocathode. Since the same type of shift appears in the mean response for both dynode orientations, it was treated as a common setup-geometry offset of the measurement coordinate.

The measured angle was corrected by applying a constant offset,

$$\theta_{\text{corr}} = \theta_{\text{meas}} - \theta_0, \quad (8.13)$$

where θ_0 is the estimated angular zero offset. The offset was determined from the symmetry of the mean spatial response and from the relative positions of the left and right photocathode-edge transitions. The resulting corrections were approximately

$$\theta_0 \simeq 5.25^\circ \quad (8.14)$$

for the dynode orientation 0° dataset and

$$\theta_0 \simeq 5.26^\circ \quad (8.15)$$

for the dynode orientation 90° dataset. The close agreement between these values supports the interpretation that the shift is caused by the common measurement geometry rather than by a dynode-orientation-dependent PMT response.

Figure 8.12 compares the normalized response before and after applying the coordinate correction. The correction aligns the left and right edge transitions more closely around the measured symmetry axis while leaving the measured QE values unchanged.

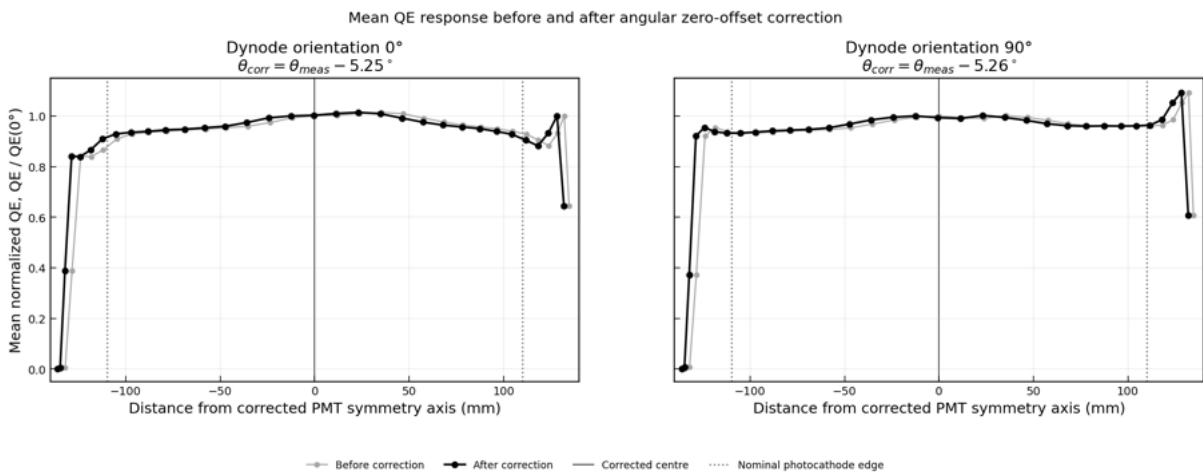


Figure 8.12: Mean normalized spatial QE response before and after angular zero-offset correction for the two dynode-orientation datasets. The correction aligns the measured angle by approximately 5.25° , aligning the response more closely with the corrected PMT symmetry axis.

After applying the correction, the spatial coordinate was recalculated using the corrected angle. Figure 8.13 compares the two dynode-orientation datasets in the common recentered coordinate.

Residual differences remain near the boundary and can now be distinguished from the common alignment displacement.

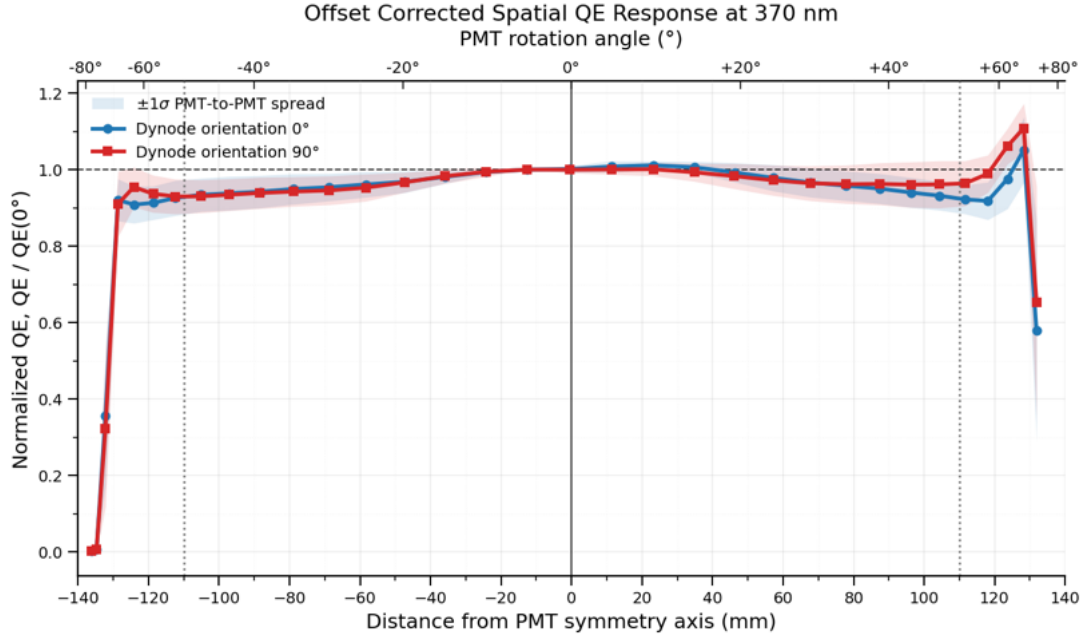


Figure 8.13: Offset-corrected normalized spatial QE response at 370 nm for dynode orientations 0° and 90° , shown using the common recentered spatial coordinate.

The correction changes only the spatial coordinate and does not modify the measured current or QE. It allows the effective left and right photocathode boundaries to be compared consistently. The remaining localized edge structure is attributed to boundary geometry, finite beam overlap, and position-dependent electron collection.

8.4.4 Understanding Dynode-Orientation Dependence

The asymmetric edge enhancement and final response fall-off motivated an additional measurement to test whether the boundary structure depended on the PMT azimuthal orientation and internal collection geometry.

PMT ST5937 was measured at four azimuthal orientations of the dynode structure: 0° , 90° , 180° , and 270° . For each orientation, the external beam path and angular-scan plane remained fixed. A finer angular spacing of 1° was used near the photocathode boundary to resolve the local maximum and the subsequent response decrease.

The spatial responses were compared using the corrected laboratory scan coordinate. Equal signed distances in the different orientation scans therefore correspond to the same side of the fixed laboratory scan direction.

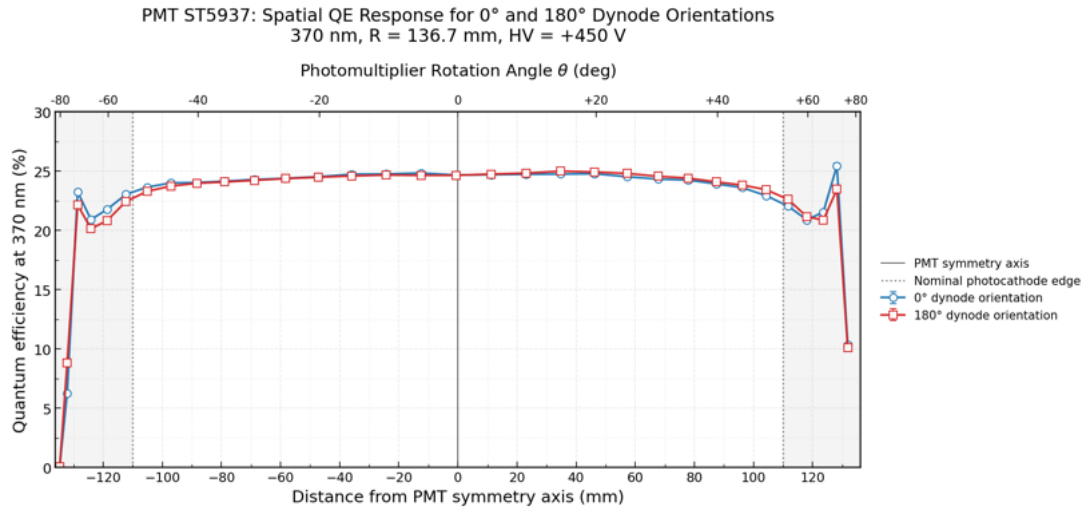


Figure 8.14: Spatial QE response of PMT ST5937 at 370 nm for dynode orientations 0° and 180° . The central responses agree closely, while differences remain in the amplitude and fall-off of the edge feature.

Figure 8.14 compares the measurements at 0° and 180° . The responses agree closely across the central photocathode region, indicating that the broad central response is largely independent of these opposite azimuthal orientations.

The main differences occur near the photocathode boundary, where the scans show different amplitudes of the local maximum and different fall-off behaviour. Because the external illumination geometry was unchanged, these differences point to an orientation-dependent contribution from the internal photoelectron-collection geometry, superimposed on the common optical response of the photocathode edge.

The edge region is shown with finer sampling in Fig. 8.15. Both orientations follow a similar response until the beam approaches the active boundary, after which the local peak height and the rate of the final decrease differ. The common edge region is mainly determined by the photocathode geometry, whereas the difference in peak amplitude indicates an additional dependence on the internal collection geometry.

The peak should not be interpreted as a direct increase in intrinsic local QE. Near the photocathode boundary, the beam footprint changes rapidly because of the curved entrance window and oblique incidence. Partial overlap with the active photocathode, internal reflections, and the trajectories of photoelectrons towards the first dynode can all change the measured current. The orientation comparison therefore identifies the edge peak as a combined optical-geometry and electron-collection effect rather than as a uniform enhancement of photocathode conversion efficiency.

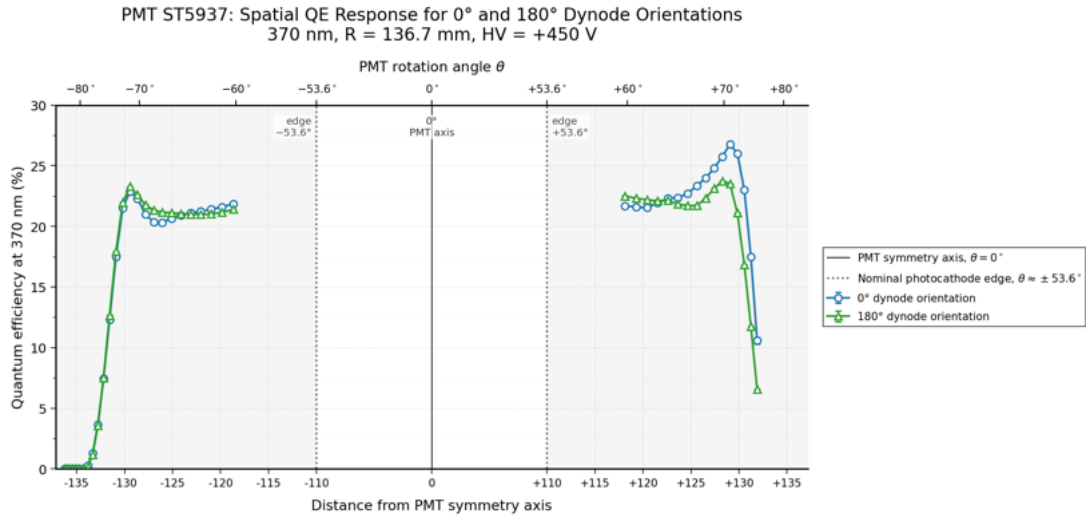


Figure 8.15: Zoomed edge-region comparison for 0° and 180° dynode orientations. The scans agree shortly before the edge enhancement, while the peak height and final fall-off differ between opposite PMT orientations.

A corresponding comparison for the 90° and 270° dynode orientations is shown in Fig. 8.16. Again, the central response remains similar, while orientation-dependent differences appear near the photocathode edge. This behaviour supports the same interpretation: the edge enhancement is not only a fixed artifact of the external measurement geometry.

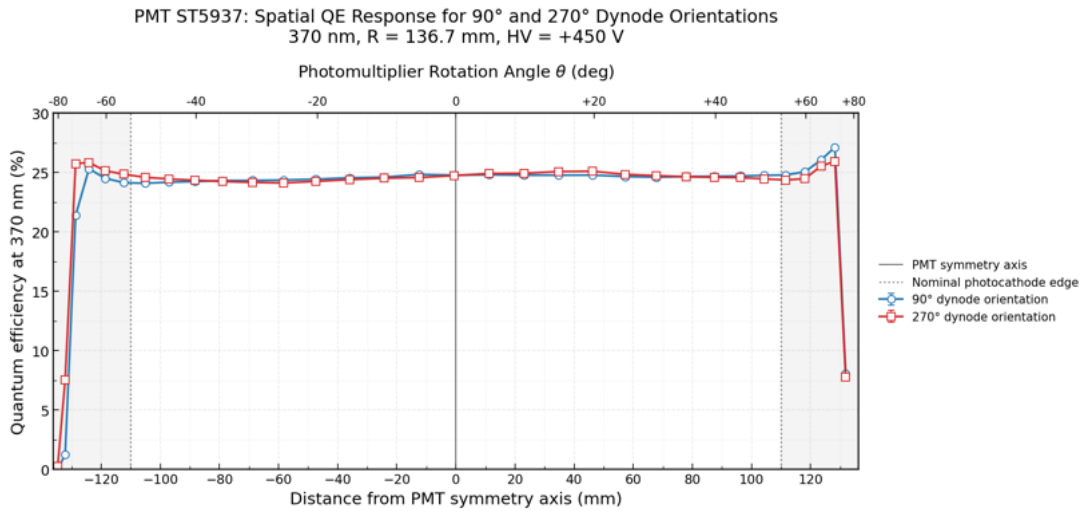


Figure 8.16: Spatial QE response of PMT ST5937 at 370 nm for 90° and 270° dynode orientations. The opposite PMT orientations show similar central response but differ in the edge-enhancement region.

The zoomed comparison in Fig. 8.17 shows that the largest differences again occur at the edge peak and during the final response drop. The behaviour is therefore consistent with the $0^\circ/180^\circ$ comparison: the central response is stable, while the edge region is sensitive to PMT orientation and local measurement geometry.

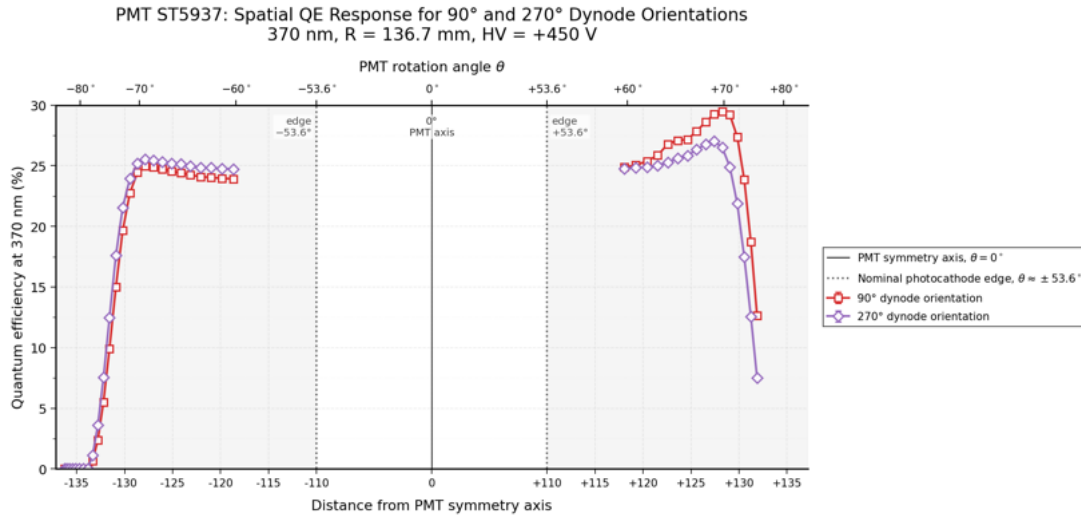


Figure 8.17: Zoomed edge-region comparison for 90° and 270° dynode orientations. The scans are consistent before the peak region, while the peak height and fall-off show orientation-dependent differences.

The opposite-orientation scans show a stable central response and orientation-dependent differences near the edge. The edge feature is therefore partly connected to the PMT geometry, most likely through the combination of photocathode-edge illumination and electron collection near the first dynode. It should not be treated as a precisely measured enhancement of useful detector sensitivity.

The useful conclusion is limited to the spatial region relevant for the present reuse assessment. The central and near-central photocathode response is stable and largely independent of dynode orientation. Orientation-dependent effects become visible mainly close to the photocathode edge, where the measurement is also most sensitive to beam overlap, reflections, zero-position uncertainty, and the exact photocathode boundary. From the present data alone, these contributions cannot be separated uniquely. For the reuse discussion, this does not change the main result: the useful photocathode region is dominated by the broad central response plateau rather than by the narrow edge-enhancement feature.

8.5 Interpretation of the Spatial QE Response

The angular-response study extends the fixed-geometry QE analysis by characterizing the photocurrent-derived response at different positions across the hemispherical photocathode. At (370 nm), the response remains broadly stable over most of the nominal photocathode region. The strongest deviations occur near the photocathode boundary, where partial beam overlap, reflections, boundary geometry, and position-dependent electron collection become more influential.

A summary of the angular measurements is shown in Fig. 8.18. For PMT ST5937, the four measured scan directions corresponding to 0°, 90°, 180°, and 270° dynode orientations were converted into a front-view representation of the photocathode surface. The measured radial points were interpolated to form a circular response map at (370 nm). The four radial directions represent the directly measured data, while the regions between them are obtained by interpolation.

PMT ST5937: Complete Photomultiplier Surface Interpolation of Quantum Efficiency at 370nm

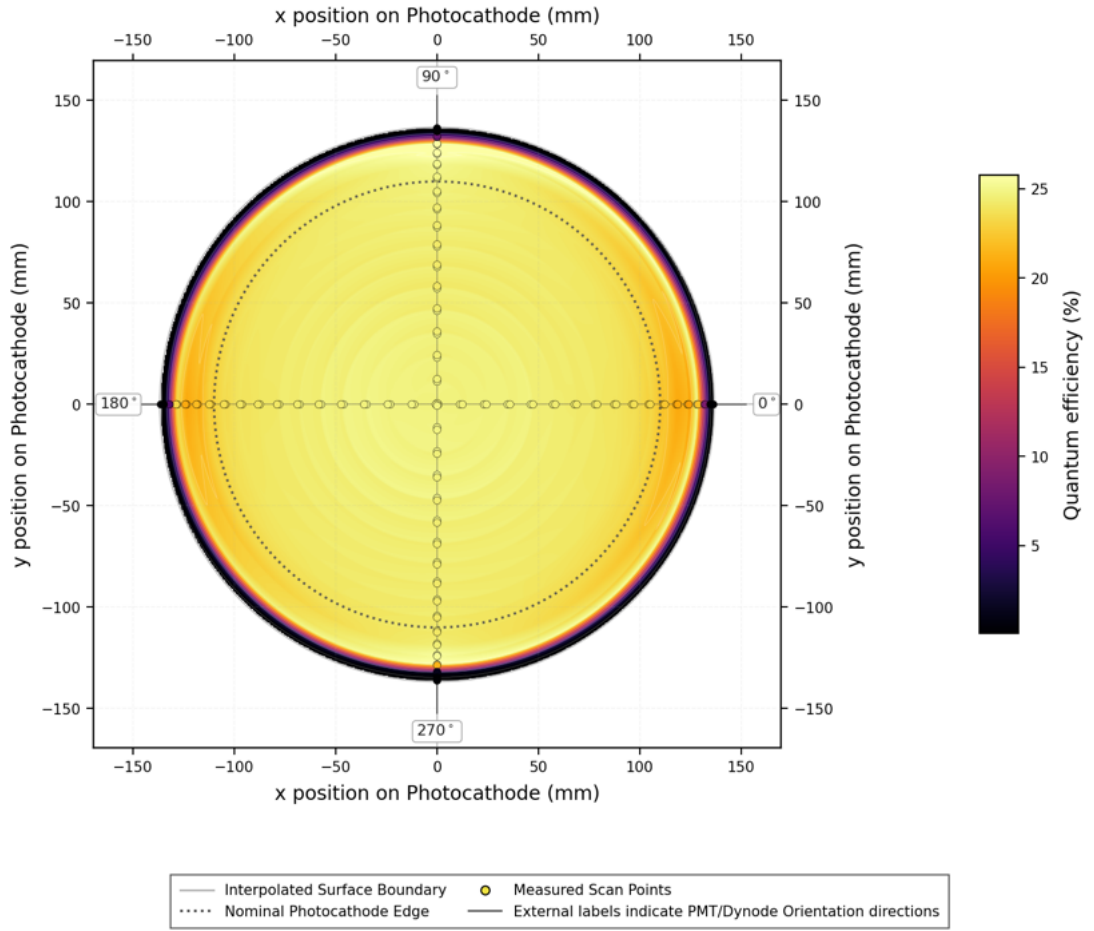


Figure 8.18: Interpolated front-view representation of the photocurrent-derived response of PMT ST5937 at (370 nm), constructed from four measured dynode-orientation scan directions. The marked radial points represent direct measurements, while the response between the measured directions is interpolated.

The interpolated representation is consistent with the individual radial scans. The central and near-central photocathode regions form a broad high-response area, with values close to the normal-incidence response. A pronounced reduction appears mainly near the outer boundary of the sensitive region. The responsive area therefore extends over a large fraction of the hemispherical photocathode rather than being restricted to a narrow region around the PMT axis.

The behaviour near the photocathode boundary is summarized in Fig. 8.19. The dedicated 0°/180° and 90°/270° comparisons show that the local edge features change when the PMT is rotated around its symmetry axis. This indicates that the observed structure is partly associated with the PMT orientation and internal geometry rather than being determined only by a fixed feature of the external setup. The response in this region is likely influenced by the combined effects of partial photocathode illumination, boundary reflections, and position-dependent electron collection.

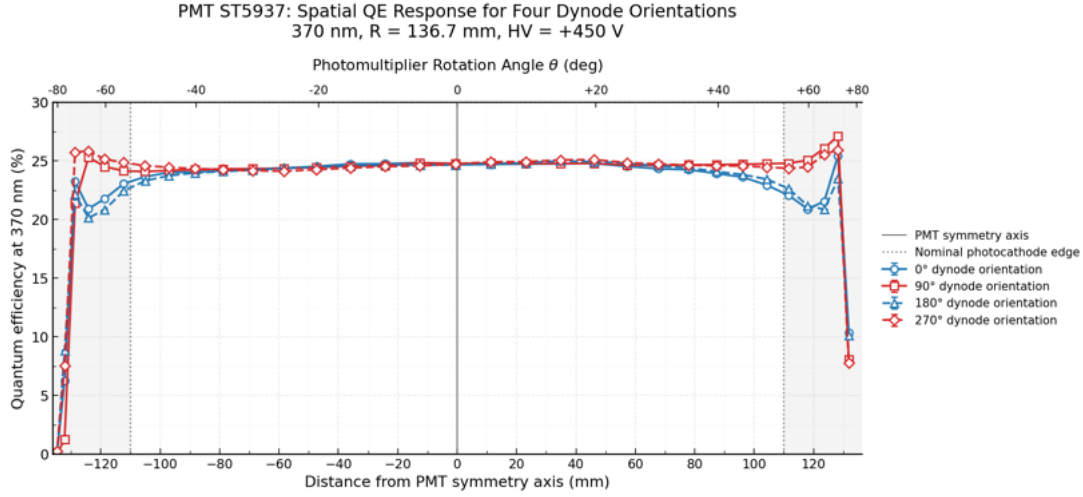


Figure 8.19: Combined dynode-orientation comparison of the edge-region response of PMT ST5937. The edge features change between opposite PMT orientations, indicating a contribution from the PMT geometry in addition to the external measurement conditions.

The measured edge transitions can also be used to estimate the effective photocathode size under the applied illumination geometry. From the spatial scans, the response decreases sharply at approximately

$$d_L \approx -132 \text{ mm}, \quad d_R \approx +132 \text{ mm}.$$

The effective photocathode diameter along the measured direction is therefore

$$D_{\text{eff}} = d_R - d_L \approx 132 \text{ mm} - (-132 \text{ mm}) = 264 \text{ mm}. \quad (8.16)$$

Assuming an approximately circular projected active boundary, the corresponding effective photocathode area is

$$A_{\text{eff}} \simeq \pi \left(\frac{D_{\text{eff}}}{2} \right)^2 = \pi (132 \text{ mm})^2 \approx 5.47 \times 10^4 \text{ mm}^2 \approx 547 \text{ cm}^2. \quad (8.17)$$

This value represents the projected active area under the applied illumination geometry rather than the curved physical surface area of the hemispherical photocathode. The estimate is approximate because the edge transition is sampled at discrete positions.

The angular scans also reveal spatial variations that are not visible in a measurement performed only at the central illumination position. Figure 8.20 shows examples of PMTs with an acceptable central response but reduced or distorted behaviour at other photocathode positions. Additional examples of moderate spatial degradation are presented in Appendix A.6. These measurements demonstrate the value of including spatial response in the characterization of large hemispherical photocathodes.

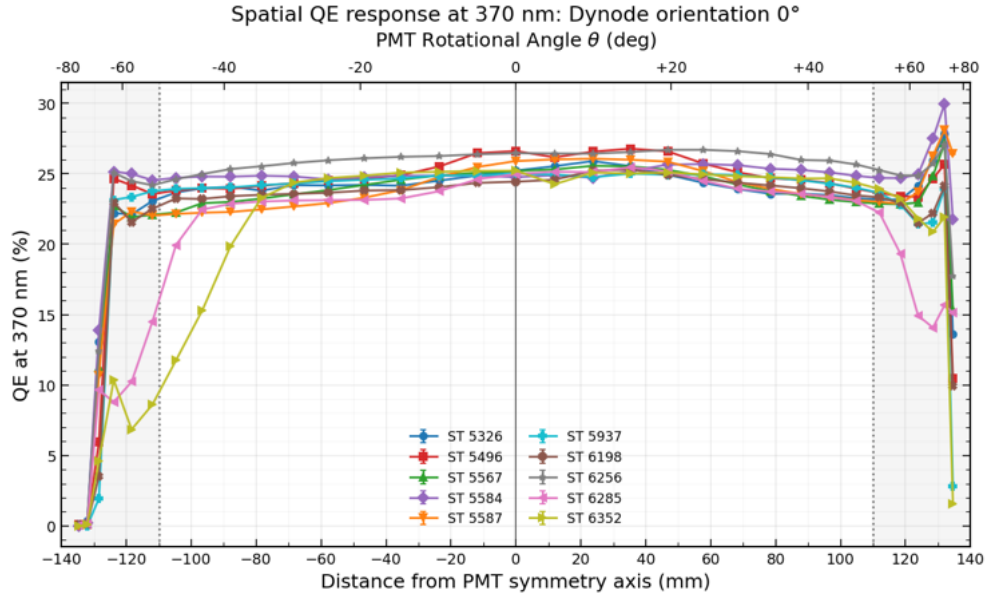


Figure 8.20: Examples of PMTs with non-uniform spatial response at (370 nm). The response near the central position remains acceptable, while reduced or distorted behaviour appears at other photocathode positions.

For the reuse assessment, the angular scans distinguish PMTs with non-uniform response inside the useful central photocathode region from tubes whose deviations are confined to the boundary. The zero-offset correction provides a common spatial coordinate for comparing opposite sides and dynode orientations without altering the measured QE values.

The radial scans constitute the direct measurements, while the circular response map interpolates only between the four measured directions. Together, these results provide a spatial qualification criterion that cannot be obtained from a single central QE spectrum.

Chapter 9

Discussion, Implications and Outlook

The detailed measurement procedures, quality-control outputs, population distributions, and angular-response figures were presented in Chapters 5–8. This chapter therefore focuses on what those results establish about the recovered ANTARES photomultiplier tubes, where the present interpretation remains limited, and which measurements are still required before detector-level reuse decisions can be made. The conclusions are intentionally QE-based: they assess the retained photocathode response but do not constitute a complete PMT acceptance test.

9.1 Reliability of the QE Assessment

A physical interpretation of the measured QE spectra requires the response of the PMT to be separated from variations introduced by the optical source, monochromator, current baseline, illumination level, and angular alignment. The dedicated stability studies in Sec. 5.3 established operating conditions under which these effects were sufficiently controlled.

The lamp-stability measurements in Sec. 5.3.4 showed that spectra acquired before completion of the xenon-lamp warm-up were not reproducible. After the adopted minimum warm-up time of 90 min, the maximum pointwise residual over the measured wavelength interval was reduced to 4.81 %, and the remaining variation was included in the optical-flux uncertainty. The corresponding measurements are shown in Figs. 5.15 and 5.16.

The monochromator transition near 400 nm produced a large change in raw optical throughput, as demonstrated in Sec. 5.3.3. However, the forced-setting comparison in Sec. 6.2.2 showed that the PMT and photodiode currents changed by similar factors and that their ratio remained nearly unchanged. The agreement of the reconstructed QE curves in Figs. 6.2 and 6.4 confirms that photodiode normalization removes most of this throughput discontinuity. Localized features near the transition were nevertheless retained as quality-control indicators because this wavelength region remains more sensitive to configuration changes and low-current effects.

Dark-current stability and photocurrent dependence were the principal PMT-specific limitations. The stabilization study in Sec. 5.3.5 justified the dedicated pre-scan dark-current acquisition, while Secs. 6.2.3 and 6.2.4 showed why unusual spectra must be checked against baseline drift and illumination level before they are interpreted as photocathode effects. A reduced spectrum was therefore treated as physically meaningful only when its baseline was stable, its wavelength dependence was plausible, and its response was reproducible under controlled acquisition conditions.

The automated and manual quality-control procedure is reported in Sec. 6.5. Its final measurement

dispositions are summarized in Table 6.2 and Fig. 6.11. Of the 124 extracted-PMT measurements, 114 produced spectra suitable for population-level physical interpretation, while 10 remained unresolved and were assigned to focused inspection or remeasurement. These categories describe confidence in the present QE measurement; they are not hardware acceptance or rejection classes.

9.2 Implications for the Recovered PMT Population

The complete population results are presented in Sec. 7.1, with the spectral distribution shown in Fig. 7.1 and the peak-QE statistics listed in Table 7.1. The population is compact and approximately centred around a common wavelength dependence. The principal tube-to-tube variation is the absolute QE level rather than a systematic change in spectral form.

The post-QC assessment in Sec. 7.3 provides the most reliable basis for physical interpretation. For the retained population, the median peak QE is approximately 25.55 %, and all retained PMTs remain above the historical ANTARES peak-QE requirement of approximately 20 % [12]. The retained spectra and the distributions of peak, mean-band, and Cherenkov-weighted QE are shown in Figs. 7.6 and 7.7. Their agreement indicates that the retained response extends across the near-ultraviolet and blue sensitivity region rather than being confined to a narrow spectral maximum.

The TM0007 comparison in Sec. 7.2 supports the same population-level interpretation. As shown in Fig. 7.4, TM0007 lies within the measured range of the extracted PMTs and shows a somewhat lower response mainly in the 400 nm to 500 nm interval. The band-resolved comparison in Table 7.2 shows that this difference is comparable to the variation observed among individual extracted PMTs. TM0007 is therefore an independent comparison tube of the same model, not an upper performance limit or a substitute for the unavailable pre-deployment spectrum of each recovered PMT.

The line and storey analyses provide no evidence for a simple deployment-location dependence. The Line 4 and Line 8 distributions and spectra in Figs. 7.13 and 7.14 largely overlap, with the wider spread of Line 4 arising from individual lower-QE tubes rather than a shift of the complete line population. Likewise, the storey-position results in Fig. 7.15 and Table 7.5 are consistent with no monotonic vertical trend. Within the available two-line sample, the present QE variation is therefore better described as PMT-specific than as a line-wide or storey-dependent effect.

Taken together, these results provide no evidence for a uniform population-wide reduction of wavelength-dependent photocathode sensitivity. They do not show that every PMT is unchanged; rather, they show that most recovered tubes still possess a strong, smooth, and physically plausible QE response after ANTARES operation and subsequent recovery and handling.

9.3 Implications of the Spatial-Response Measurements

The angular measurements extend the central spectral scan by probing different regions of the hemispherical photocathode. The wavelength–angle maps in Fig. 8.5 show that changing the illuminated position primarily changes the response amplitude while leaving the broad spectral form intact. At 370 nm, the normalized sample comparison in Fig. 8.11 shows a broad central response region followed by a rapid change near the photocathode boundary.

The zero-offset analysis in Sec. 8.4.3 demonstrated that the displaced edge transitions originated mainly from the common measurement coordinate. Recentring the angular position aligned the two sides of the response without modifying the measured current or QE, as shown in Figs. 8.12 and 8.13. Under the applied illumination geometry, the corrected edge transitions correspond to an effective projected responsive diameter of approximately 264 mm and the corresponding

effective photocathode area is approximately 547 cm^2 . This value characterizes the projected response in the laboratory scan and should not be interpreted as the curved physical photocathode area.

The opposite-orientation comparisons in Figs. 8.14 and 8.16 show closely matching central responses but different edge maxima and fall-off behaviour. The boundary response therefore contains contributions from both the external optical geometry and the internal photoelectron-collection geometry. Localized edge enhancements cannot be interpreted as a direct increase in intrinsic photocathode QE.

For reuse qualification, the central and near-central response is more informative than the narrow edge feature. A tube with a stable central response but geometry-dependent behaviour only at the boundary is different from a tube with reduced or distorted response inside the useful photocathode region. The examples in Fig. 8.20 also show that an acceptable central QE value does not guarantee spatial uniformity. Spatial characterization therefore provides information that cannot be obtained from a single central spectral scan.

9.4 Next Steps for Reuse Qualification

Combined PMT Qualification

The QE results should be integrated with the electrical, noise, stability, timing, and pulse-response measurements of the wider reuse programme. Each PMT should have a common qualification record linking its spectral QE, spatial-response result, measurement caveats, and complementary operating characteristics. This combined record would distinguish tubes with genuinely weak detector response from tubes whose QE remains useful but whose suitability is limited by another performance parameter.

Detector-Level Validation

The measured spectral curves and spatial-response maps can be included in optical simulations of candidate SWGO water Cherenkov detector units. Such simulations would determine whether the observed PMT-to-PMT differences produce meaningful changes in photoelectron yield, triggering, timing, or event reconstruction under realistic photon distributions. Prototype measurements with selected recovered PMTs should then test these predictions under detector operating conditions.

9.5 Overall Assessment

The present work converts the recovered ANTARES PMTs from a population with an uncertain post-recovery photocathode condition into a measured and quality-controlled QE population. Most tubes retain a strong wavelength-dependent response, the retained population shows no common spectral suppression relative to the available comparison levels, and the angular measurements show that the useful central photocathode region is generally stable in the investigated subset.

From a QE perspective, the recovered PMTs therefore form a strong candidate population for further SWGO reuse qualification. Final selection should be made only after the unresolved measurements have been addressed and the QE results have been combined with broader spatial, electrical, timing, noise, simulation, and prototype-detector assessments.

Acronyms

ANTARES Astronomy with a Neutrino Telescope and Abyss environmental RESearch.

CE collection efficiency.

CSV comma-separated values.

CTA Cherenkov Telescope Array.

DLL dynamic-link library.

EAS extensive air shower.

FWHM full width at half maximum.

H.E.S.S. High Energy Stereoscopic System.

HAWC High-Altitude Water Cherenkov Observatory.

IACT imaging atmospheric Cherenkov telescope.

LED light-emitting diode.

LHAASO Large High Altitude Air Shower Observatory.

MAD median absolute deviation.

MSH monochromator system housing.

OM optical module.

PCA principal component analysis.

PMT photomultiplier tube.

QC quality control.

QE quantum efficiency.

SWGO Southern Wide-field Gamma-ray Observatory.

TMCL Trinamic Motion Control Language.

TTS transit-time spread.

UV ultraviolet.

VHE very-high-energy.

WCD water Cherenkov detector.

Appendix A

Supplementary Material

A.1 Dark-Current Stabilization Examples

Figure A.1 shows representative dark-current stabilization measurements for selected extracted ANTARES PMTs. These examples illustrate the relaxation behaviour observed after the PMT was prepared for measurement and before the final stable dark-current value was used for correction. The vertical dashed line marks the estimated start of the stable region, while the dotted horizontal line indicates the final mean dark current. These plots support the dark-current treatment discussed in Chapter 5.

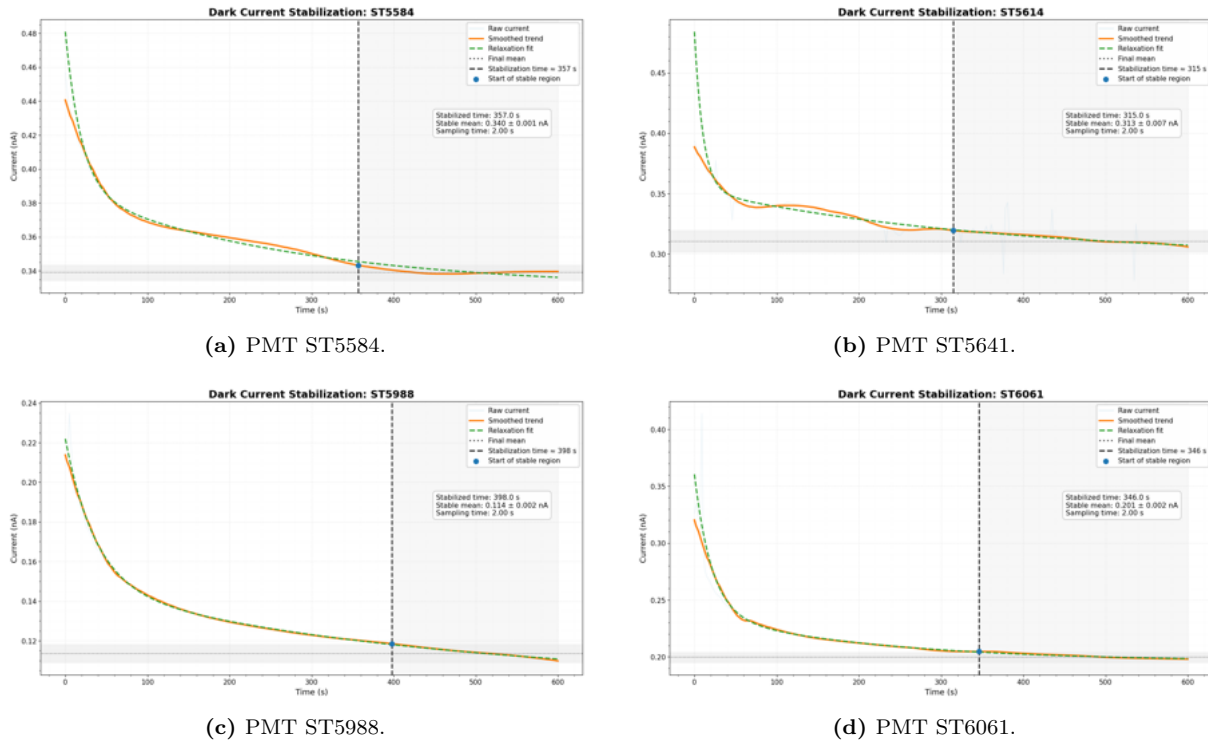


Figure A.1: Representative dark-current stabilization measurements for selected extracted ANTARES PMTs. The raw current, smoothed trend, relaxation fit, final mean current, and estimated stabilization time are shown for each PMT. These examples demonstrate why a stabilization period and explicit dark-current correction were necessary before interpreting the photocurrent measurements.

A.2 Angular QE Measurement Procedure

Figure A.2 summarizes the operational workflow used for the angular QE measurements. The diagram includes the preparation of the PMT and optical setup, pre-measurement checks, dark-current acquisition, wavelength scan sequence, angular-stage movement, post-dark measurement, and the corresponding photodiode reference measurement. It is included as supplementary procedural documentation for the measurement workflow described in Chapter 8.

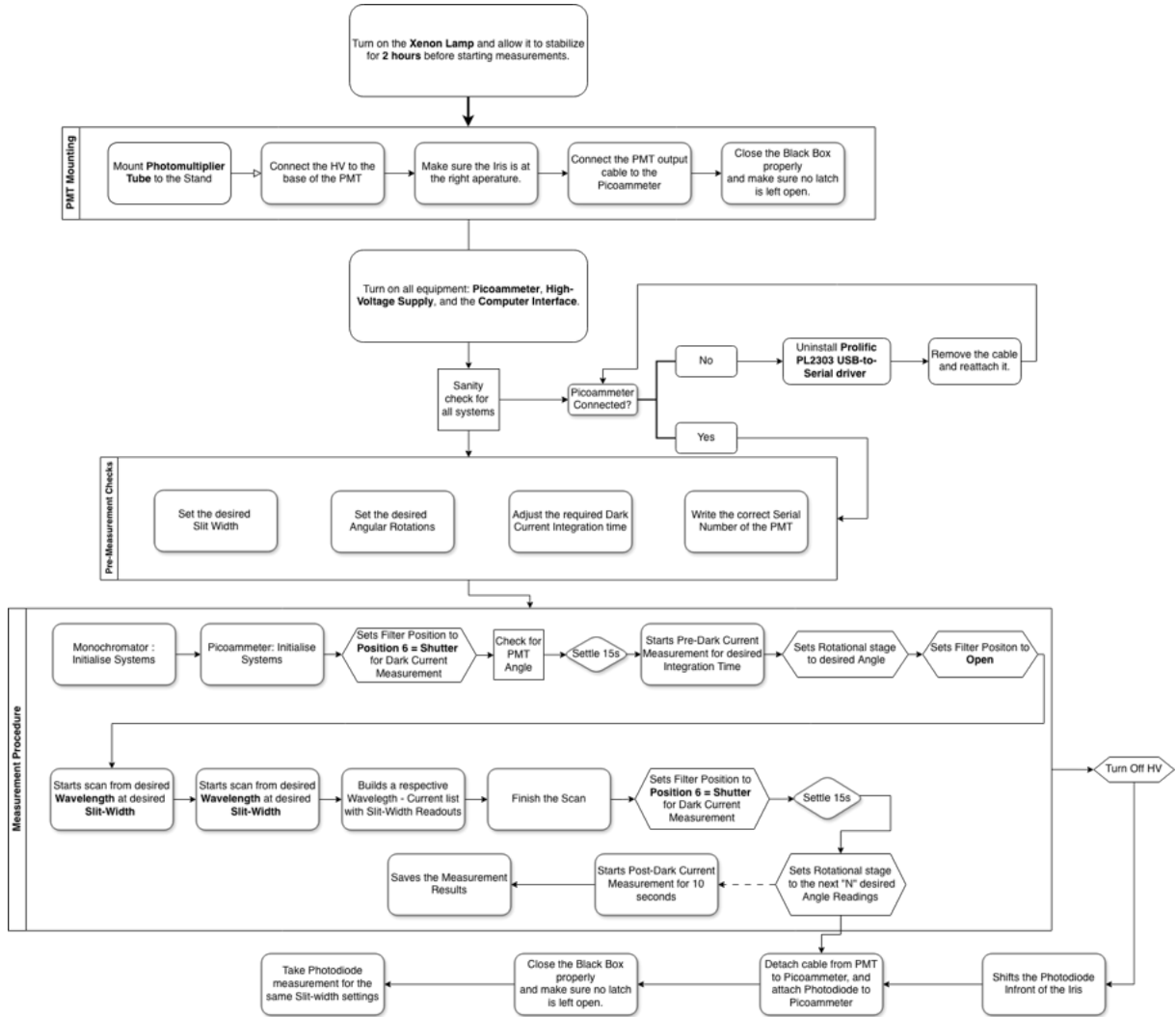


Figure A.2: Operational workflow for the angular QE measurement procedure. The flowchart summarizes PMT mounting, system checks, monochromator and picoammeter initialization, pre-dark and post-dark current measurements, angular-stage movement, wavelength scanning, data saving, and photodiode reference measurement.

A.3 Autosaving, Emergency Saving, and Reproducibility

Because angular scans were long automated measurements, the scripts included autosaving after each important step. The output table was written through an atomic-save procedure, where a temporary file was written first and then moved to the final autosave filename. This reduced the risk of losing data or producing partially written CSV files during an interruption.

If the scan was stopped manually or crashed unexpectedly, the available results were saved to a timestamped emergency file. The cleanup routine then attempted to close the shutter, return the rotation stage to 0° , close the picoammeter connection, disconnect the rotation stage, and close the monochromator DLL. The filenames encoded the PMT tag, wavelength range, angular range, slit-width segments, and timestamp, making each measurement file traceable to its experimental configuration.

A.4 Ranked PMT Quantum-Efficiency Summary

Table A.1: Ranked extracted ANTARES PMTs based on first-stage optical reuse relevance. The ranking is ordered by QC tier (GOLD, SILVER, BRONZE, REVIEW) and, within each tier, by Cherenkov-weighted QE, mean QE in the 300–500 nm band, and peak QE. The OM status column gives the available ANTARES optical-module status metadata: “.” denotes a module with available nominal rate information, “O” denotes a module for which no rate information was available, “X” denotes an undefined status, and “M” denotes that the serial number is missing in the OM data file.

Rank	Serial	Peak QE (%)	OM status	QC tier	Mean QE 300–500 nm (%)	Cherenkov-weighted QE 300–500 nm (%)
1	ST5496	26.29	.	GOLD	21.83	21.34
2	ST5251	26.35	.	GOLD	21.63	21.17
3	ST5587	26.07	.	GOLD	21.53	21.11
4	ST5578	25.90	.	GOLD	21.14	20.80
5	ST5332	26.28	M	GOLD	21.21	20.60
6	ST5502	25.22	O	GOLD	20.91	20.57
7	ST5588	25.50	O	GOLD	20.93	20.43
8	ST5428	26.28	X	GOLD	21.13	20.41
9	ST6008	26.45	M	GOLD	21.18	20.39
10	ST5567	25.69	.	GOLD	20.93	20.31
11	ST5558	25.94	.	GOLD	20.93	20.12
12	ST5584	25.14	.	GOLD	20.68	20.11
13	ST6331	25.76	.	GOLD	20.79	20.10
14	ST6020	25.08	.	GOLD	20.52	20.05
15	ST5504	25.72	.	GOLD	20.47	19.87
16	ST6280	25.44	X	GOLD	20.38	19.75
17	ST6267	25.01	.	GOLD	20.17	19.63
18	ST5451	24.95	O	GOLD	20.19	19.61
19	ST5937	24.97	O	GOLD	20.20	19.59
20	ST5813	24.90	.	GOLD	20.10	19.47
21	ST6368	25.85	.	GOLD	20.36	19.44
22	ST6053	25.76	.	GOLD	20.39	19.39
23	ST5326	25.24	.	GOLD	20.10	19.37
24	ST6198	24.22	.	GOLD	19.73	19.27
25	ST5420	24.95	M	GOLD	19.91	19.11
26	ST6285	25.23	.	GOLD	19.89	19.08
27	ST6272	24.81	.	GOLD	19.75	18.97
28	ST5239	24.87	O	GOLD	19.68	18.83
29	ST5815	24.61	.	GOLD	19.42	18.67
30	ST6093	24.58	O	GOLD	19.38	18.59
31	ST5277	24.81	.	GOLD	19.43	18.54
32	ST5329	27.29	.	SILVER	22.46	21.88
33	ST6256	26.32	X	SILVER	22.05	21.66
34	ST5582	25.74	.	SILVER	21.25	20.81

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Table A.1: Ranked extracted ANTARES PMTs based on first-stage optical reuse relevance continued.

Rank	Serial	Peak QE (%)	OM status	QC tier	Mean QE 300–500 nm (%)	Cherenkov-weighted QE 300–500 nm (%)
35	ST5313	25.67	O	SILVER	21.18	20.72
36	ST5628	26.15	.	SILVER	21.10	20.59
37	ST6300	26.13	.	SILVER	21.19	20.48
38	ST5299	26.19	.	SILVER	21.14	20.38
39	ST6233	26.24	O	SILVER	21.03	20.35
40	ST5331	26.08	.	SILVER	21.00	20.24
41	ST5555	25.53	.	SILVER	20.91	20.24
42	ST5172	26.48	.	SILVER	21.04	20.09
43	ST5348	26.24	.	SILVER	20.90	19.95
44	ST6332	26.54	.	SILVER	20.96	19.92
45	ST5289	25.83	.	SILVER	20.56	19.72
46	ST5741	25.32	X	SILVER	20.32	19.70
47	ST6030	25.62	.	SILVER	20.41	19.63
48	ST5614	25.34	X	SILVER	20.32	19.61
49	ST6352	25.46	O	SILVER	20.11	19.18
50	ST5848	23.81	.	SILVER	19.46	19.08
51	ST6239	25.73	.	SILVER	20.12	19.07
52	ST5600	24.35	O	SILVER	19.60	19.05
53	ST6304	25.57	.	SILVER	19.96	18.99
54	ST6340	25.17	O	SILVER	19.55	18.52
55	ST6236	24.81	.	SILVER	19.38	18.38
56	ST6278	24.24	.	SILVER	19.21	18.25
57	ST5626	26.12	.	BRONZE	21.62	21.09
58	ST5818	26.50	.	BRONZE	21.59	20.87
59	ST6069	26.64	.	BRONZE	21.60	20.84
60	ST5484	26.17	.	BRONZE	21.44	20.83
61	ST5426	25.35	.	BRONZE	20.98	20.71
62	ST5543	25.37	.	BRONZE	20.98	20.61
63	ST5324	26.39	O	BRONZE	21.31	20.53
64	ST5295	27.18	.	BRONZE	21.49	20.48
65	ST5988	25.89	.	BRONZE	20.89	20.32
66	ST5168	25.45	.	BRONZE	20.68	20.08
67	ST5169	26.24	O	BRONZE	20.85	20.08
68	ST5315	25.83	O	BRONZE	20.74	19.97
69	ST5986	26.17	.	BRONZE	20.67	19.79
70	ST5562	24.96	.	BRONZE	20.09	19.50
71	ST5356	25.67	.	BRONZE	20.31	19.43
72	ST5784	24.16	.	BRONZE	19.62	19.20
73	ST5455	24.25	.	BRONZE	19.64	19.17
74	ST5564	24.43	.	BRONZE	19.50	19.09
75	ST5728	24.54	.	BRONZE	19.58	19.01
76	ST6046	24.91	.	BRONZE	19.80	18.97
77	ST6061	24.38	.	BRONZE	19.50	18.93
78	ST6271	24.63	.	BRONZE	19.62	18.89
79	ST5690	25.40	.	BRONZE	19.80	18.81
80	ST6262	24.57	.	BRONZE	19.61	18.79
81	ST5987	24.71	O	BRONZE	19.25	18.60
82	ST6191	23.55	.	BRONZE	18.82	18.17
83	ST6327	24.35	.	BRONZE	19.12	18.13
84	ST5311	23.87	.	BRONZE	18.70	18.12
85	ST6345	23.29	.	BRONZE	18.51	17.90
86	ST5938	22.84	.	BRONZE	18.13	17.35
87	ST6210	28.57	.	REVIEW	23.99	23.43
88	ST5547	28.12	.	REVIEW	23.76	23.18
89	ST6025	29.01	.	REVIEW	23.42	22.57
90	ST5590	27.60	.	REVIEW	22.99	22.57
91	ST5253	27.57	.	REVIEW	22.88	22.45
92	ST6350	28.89	.	REVIEW	22.87	22.20
93	ST6003	26.83	O	REVIEW	22.20	21.57
94	ST5996	26.81	.	REVIEW	22.13	21.49
95	ST5498	26.02	O	REVIEW	21.63	21.30
96	ST5649	26.51	O	REVIEW	21.65	21.26
97	ST5306	27.55	O	REVIEW	22.02	21.09
98	ST5022	26.27	.	REVIEW	21.46	20.79
99	ST5225	27.16	.	REVIEW	21.67	20.63
100	ST6317	27.25	.	REVIEW	21.63	20.61

Continued on next page

Table A.1: Ranked extracted ANTARES PMTs based on first-stage optical reuse relevance continued.

Rank	Serial	Peak QE (%)	OM status	QC tier	Mean QE 300–500 nm (%)	Cherenkov-weighted QE 300–500 nm (%)
101	ST5810	26.18	.	REVIEW	21.14	20.55
102	ST6263	26.05	O	REVIEW	21.02	20.45
103	ST5529	25.19	.	REVIEW	20.79	20.41
104	ST5228	26.82	.	REVIEW	21.23	20.36
105	ST5985	26.81	O	REVIEW	21.36	20.23
106	ST5211	27.05	.	REVIEW	21.16	20.11
107	ST6012	25.48	.	REVIEW	20.73	20.02
108	ST5403	25.43	.	REVIEW	20.70	20.01
109	ST5663	25.98	.	REVIEW	20.72	19.97
110	ST6290	26.61	.	REVIEW	20.55	19.48
111	ST5402	25.07	O	REVIEW	20.06	19.47
112	ST6023	24.73	.	REVIEW	19.80	19.14
113	ST6241	24.97	O	REVIEW	19.54	18.97
114	ST6277	24.43	.	REVIEW	19.61	18.96
115	ST5170	24.19	.	REVIEW	19.08	18.65
116	ST6270	22.96	.	REVIEW	18.28	17.92
117	ST5830	22.91	.	REVIEW	18.49	17.86
118	ST5407	24.86	.	REVIEW	18.00	17.42
119	ST6228	24.16	.	REVIEW	18.24	17.00
120	ST6282	23.67	.	REVIEW	17.79	16.72
121	ST6344	22.31	O	REVIEW	17.52	16.72
122	ST6195	22.71	.	REVIEW	17.39	16.36
123	ST5593	20.12	.	REVIEW	16.71	16.29
124	ST6213	19.33	.	REVIEW	15.11	14.78

A.5 REVIEW Quality-Control Spectra

Figures A.3–A.7 show all 38 extracted ANTARES PMT measurements classified in the REVIEW category by the automated quality-control pipeline. These spectra are included as supplementary diagnostic material because they exhibit features that warranted manual inspection, including deviations from the population spectral shape, boundary-region distortions, low-QE behaviour, or other measurement-sensitive features. Assignment to REVIEW therefore does not by itself imply rejection of the measurement, but identifies spectra requiring further assessment before inclusion in the final physical interpretation.

Of the REVIEW-category measurements shown below, 10 were excluded from the final population-level physical interpretation and were instead assigned for remeasurement or focused inspection. These PMTs were:

ST5407, ST5593, ST6025, ST6213, ST6228, ST6241, ST6263, ST6282, ST6290, and ST6350.

The remaining REVIEW-category spectra were retained after manual inspection with an appropriate measurement caveat, as discussed in Section 6.5.

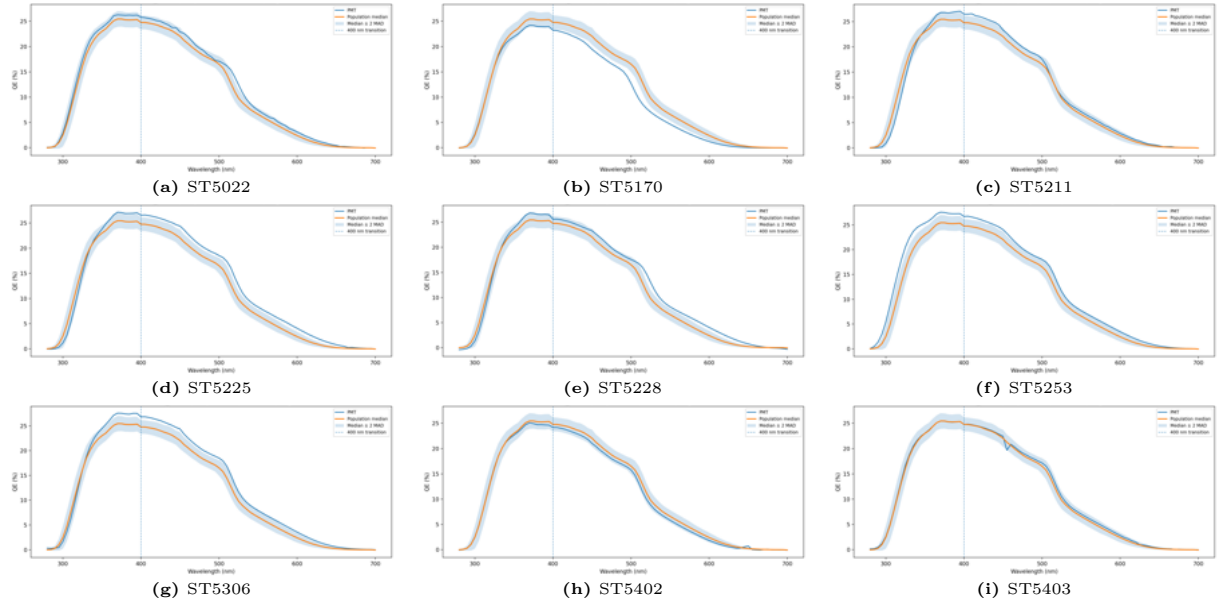


Figure A.3: REVIEW-category quality-control spectra, part 1.

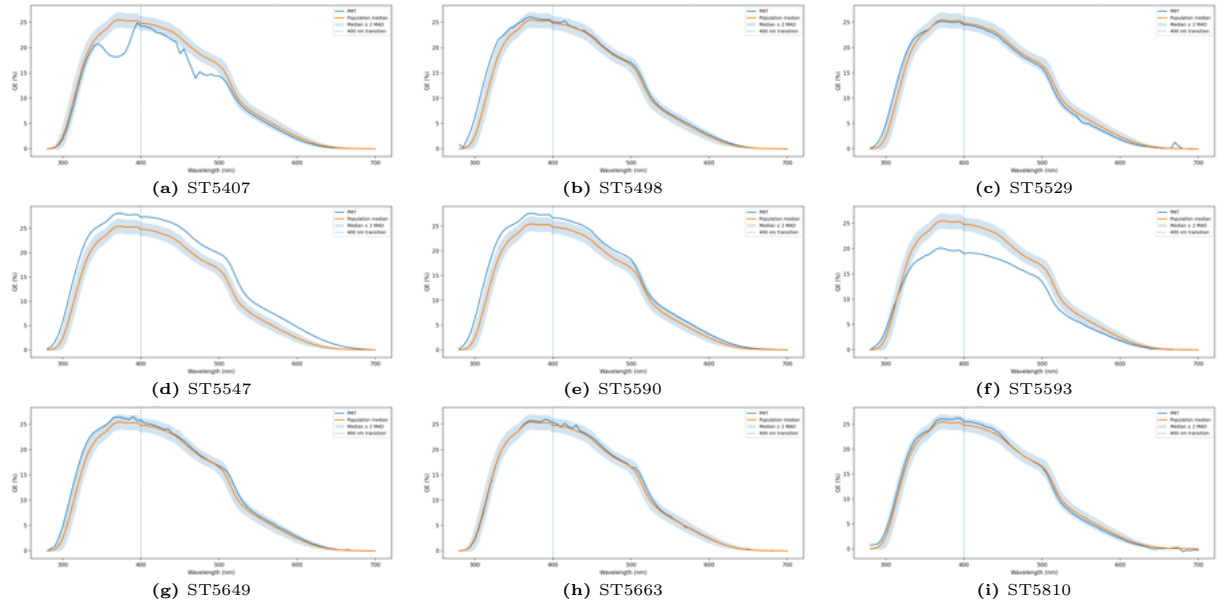


Figure A.4: REVIEW-category quality-control spectra, part 2.

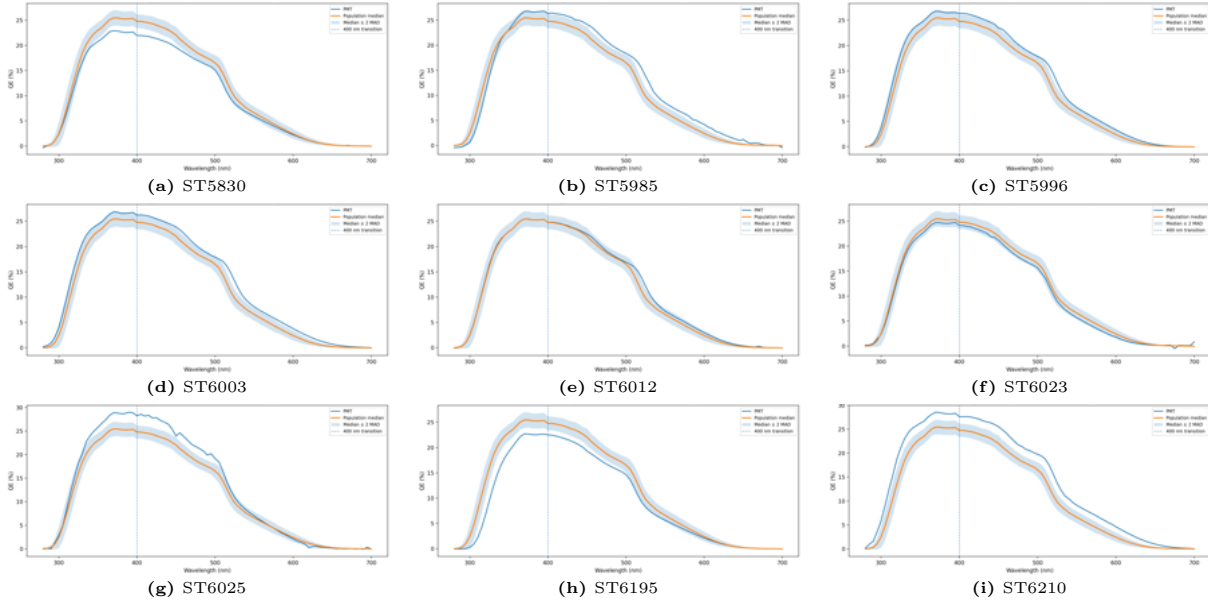


Figure A.5: REVIEW-category quality-control spectra, part 3.

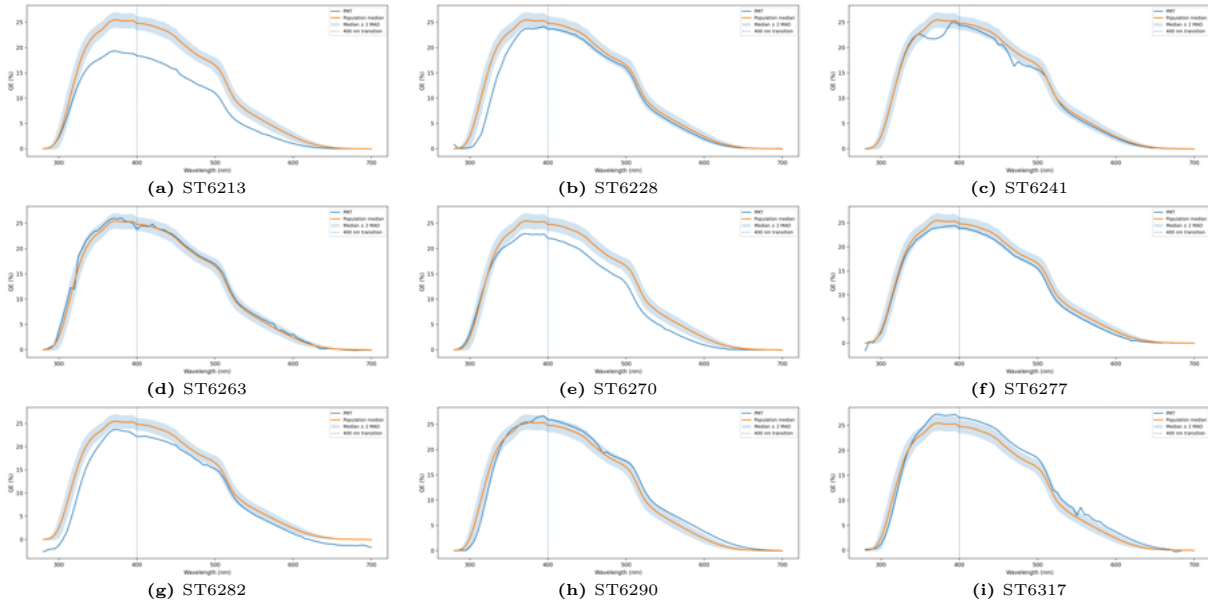


Figure A.6: REVIEW-category quality-control spectra, part 4.

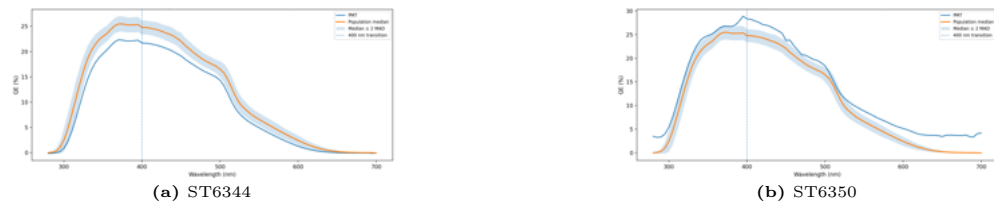


Figure A.7: REVIEW-category quality-control spectra, part 5. The REVIEW classification identifies measurements requiring manual inspection and does not constitute an automatic rejection of the corresponding PMT.

A.6 Mild Spatial Degradation

Figures A.8 and A.9 show two representative PMTs, ST6285 and ST6352, with mild spatial non-uniformity in the QE response at 370 nm. Although both PMTs retain an acceptable central response, the QE decreases more clearly toward the photocathode edge. These examples illustrate that a satisfactory central QE value does not automatically imply uniformly good response across the full active photocathode area. They therefore support the conclusion that spatial/angular QE measurements are an important qualification step before any final PMT deployment decision.

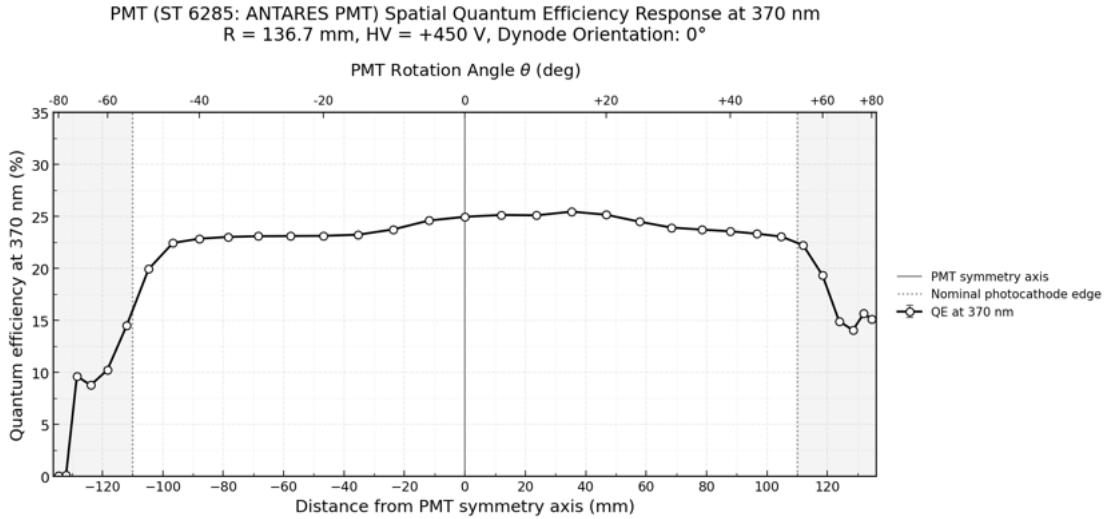


Figure A.8: Spatial QE response of PMT ST6285 at 370 nm. The PMT retains a reasonably stable central response, but shows a stronger reduction toward the photocathode edge, indicating mild spatial degradation or non-uniformity.

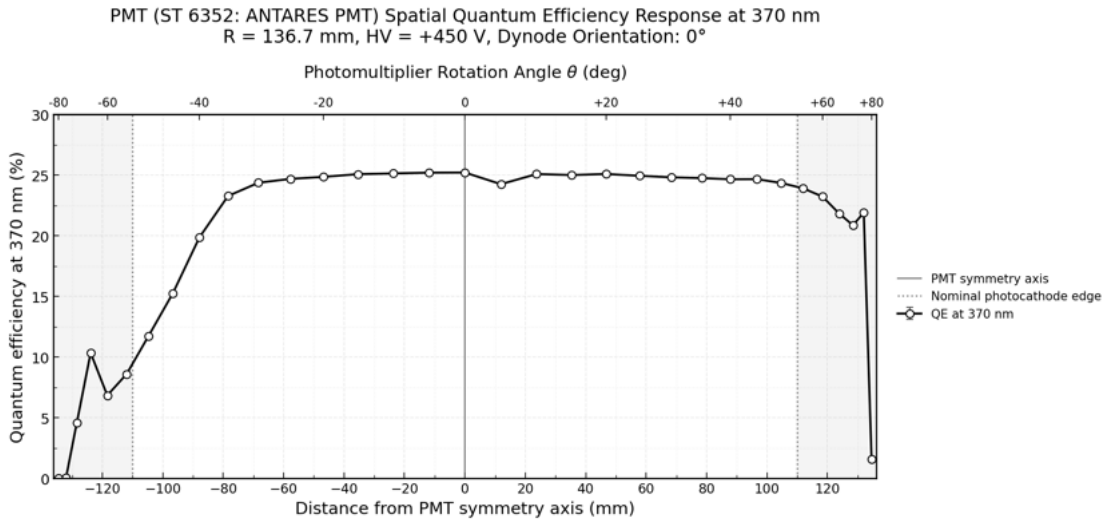


Figure A.9: Spatial QE response of PMT ST6352 at 370 nm. As for ST6285, the central response remains acceptable, while the edge-region behaviour shows a more pronounced drop, supporting the need for spatial/angular qualification before deployment.

A.7 Control Scripts and Quality Control Pipeline

The control scripts and quality-control pipeline developed and used in this thesis are available in the following Git repository:

`https://github.com/saujanyadubale/
Quantum-Efficiency-Setup-Control-Scripts-and-Quality-Control-Pipeline.git`

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Declaration of Originality

I, **Saujanya Dubale**, student registration number: 23148509, hereby confirm that I completed the submitted work independently and without the unauthorized assistance of third parties and without the use of undisclosed and, in particular, unauthorized aids. This work has not been previously submitted in its current form or in a similar form to any other examination authorities and has not been accepted as part of an examination by any other examination authority.

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