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Zurich^{UZH}**

PMT characterization and commissioning of a gaseous xenon detector for the development of new intrinsic calibration sources for liquid xenon TPCs

Bachelor Thesis in Physics

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Abstract

Liquid xenon detectors are widely used in rare-event detection, including direct dark matter detection, searches for neutrinoless double-beta decay ($0\nu\beta\beta$), and measurements of other rare nuclear decays. Future experiments are expected to contain several tens of tonnes of xenon, which introduces new challenges for the calibration of the detector volume. Radioactive noble gases are interesting as internal calibration sources because they can be mixed with xenon and distributed throughout the detector. The isotope ^{79}Kr is a possible candidate for such a calibration source because it is a noble gas with a relatively short half-life and decays through electron-capture and positron-emission branches. The resulting event signatures can be used to study the reconstruction of multi-site events relevant for searches for rare double-weak decay processes in xenon.

This thesis focuses on the preparation and commissioning of a gaseous xenon detector for future measurements with ^{79}Kr . The work was divided into the characterization and selection of suitable photomultiplier tubes and the construction of a small detector for the measurement of xenon scintillation light. Four Hamamatsu R8520 photomultiplier tubes were investigated using gain and afterpulse measurements at different operating voltages. For the gain measurements, single-photoelectron charge spectra were analysed and fitted to determine the gain of each PMT. All four PMTs showed the expected increase in gain with increasing high voltage. At higher voltages, the single-photoelectron peak became more clearly separated from the electronic baseline, and the relative width of the single-photoelectron distribution decreased, indicating an improved single-photoelectron resolution.

The afterpulse behaviour of the PMTs was investigated by studying delayed signals following the initial light pulse. Clear differences between the individual PMTs were observed. Most afterpulses occurred at short delay times and had pulse areas below 2 PE. Two PMTs showed lower total afterpulse rates while maintaining stable gain behaviour. Since afterpulses can produce additional signals that may be interpreted as scintillation light, both the gain and afterpulse measurements were considered when selecting the two PMTs for the detector.

The two selected PMTs were then used for the assembly of a small cross-shaped detector. In this design, two PMTs mounted opposite each other observe the same gaseous xenon volume. The detector was assembled and integrated into an existing gaseous xenon circulation system. Purified xenon can continuously flow through the active detector volume, while the pressure and gas flow can be monitored using the installed pressure transducer and flow meter. The setup also allows $^{83\text{m}}\text{Kr}$ and later ^{79}Kr to be introduced into the xenon circulation loop without changing the detector configuration.

The detector is intended for future measurements of scintillation signals from ^{79}Kr decays in gaseous xenon and for testing the source handling and injection procedure before measurements in a liquid xenon time projection chamber. This work completes the PMT selection and detector preparation needed before the first ^{79}Kr measurements can be carried out in the cross detector.

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AI Declaration

Artificial intelligence tools were used during the preparation of this thesis to support language correction. ChatGPT was also used as support when working on Python analysis scripts and solving programming problems. All suggestions were reviewed and adapted by the author. The author takes full responsibility for the content and results presented in this thesis.

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Part I

Introduction

Liquid xenon detectors are among the most important technologies for modern rare-event searches in particle physics. This thesis focuses on the preparation and commissioning of a detector setup for future studies of radioactive calibration sources in xenon, with a particular focus on ^{79}Kr .

2 Motivation

This thesis is motivated by the increasing size and sensitivity of future liquid xenon experiments such as XLZD [1]. These next-generation detectors are designed to study rare physical processes with very low background levels and precise event reconstruction. As the size and sensitivity of these detectors increase, detector calibration also becomes more challenging [2, 3].

2.1 Dark Matter and its Direct Detection

One of the main scientific goals of next-generation xenon detectors is the direct detection of dark matter. Observations from astrophysics and cosmology show that ordinary visible matter makes up only a small fraction of the total matter content of the Universe [4]. A much larger fraction consists of dark matter, which does not interact electromagnetically and therefore cannot be observed directly with light [5, 6].

One of the most studied dark matter candidates is the class of Weakly Interacting Massive Particles (WIMPs). In liquid xenon detectors, WIMPs are expected to scatter elastically off xenon nuclei and produce very small nuclear recoil signals. Since the expected interaction rate is extremely low, dark matter experiments require detectors with ultra-low background levels and very good signal reconstruction capabilities [5, 7].

Liquid xenon time projection chambers (TPCs) are well suited for these searches because they combine large target masses with low background levels and good event reconstruction [7, 8].

2.2 Dual-Phase Xenon TPCs

Dual-phase liquid xenon TPCs are widely used in rare-event searches, such as direct dark matter searches and searches for neutrinoless double-beta decay ($0\nu\beta\beta$). They detect both scintillation light and ionization electrons produced by particle interactions in liquid xenon. The basic working principle of a dual-phase liquid xenon TPC is shown in Figure 1.

When a particle interacts inside the liquid xenon, it excites and ionizes xenon atoms. The excited xenon atoms produce prompt scintillation light, which is called the S1 signal. At the same time, ionization electrons are released and drift upwards in an electric field towards the gaseous xenon region at the top of the detector.

At the liquid-gas interface, the electrons are extracted into the gas phase by a stronger electric field. There they produce a second scintillation signal, called S2. The amount of S2 light is proportional to the number of ionization electrons that reach the liquid-gas interface and are extracted into the gas phase. Both the S1 and S2 signals are detected by photomultiplier tubes (PMTs) placed above and below the active detector volume [9].

The time difference between S1 and S2 gives the vertical z-position of the interaction, while the distribution of the S2 light on the top PMT array allows for the reconstruction of the

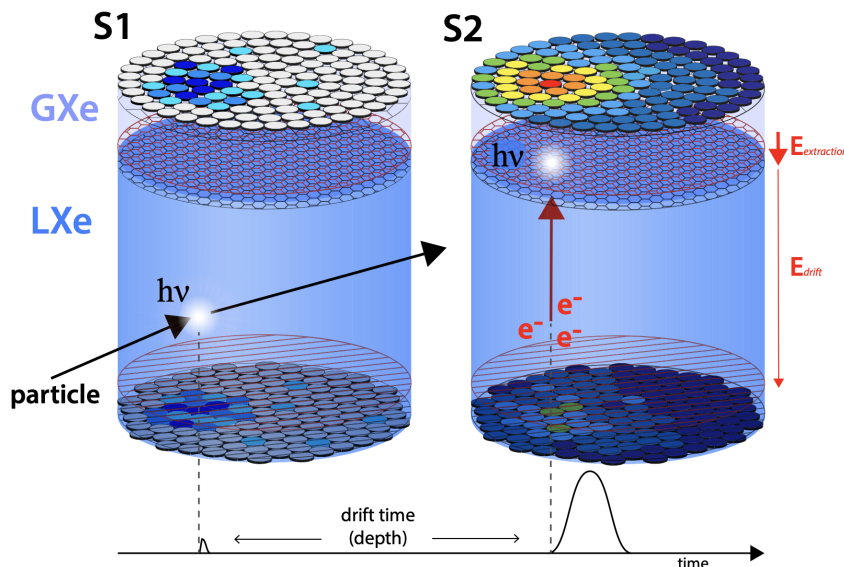


Figure 1: Simplified schematic of a dual-phase liquid xenon time projection chamber (TPC). A particle interaction inside the liquid xenon produces prompt scintillation light (S1) and ionization electrons. The electrons drift upward in an electric field and generate a delayed scintillation signal (S2) in the gaseous xenon region. The ratio between S1 and S2 can be used to distinguish between nuclear recoils and electronic recoils. Figure from [10].

horizontal x-y position. In this way, the interaction position can be reconstructed in three dimensions. This helps to reduce background because events close to the detector walls can be removed from the analysis. In addition, events can be selected or rejected based on whether they have a single-site or multi-site topology.

The ratio between the S2 and S1 signals is different for electronic recoils and nuclear recoils and can therefore be used for background discrimination in dark matter searches. Nuclear recoils usually produce a smaller S2/S1 ratio than electronic recoils [9].

The capability to reconstruct several separated interaction sites also makes liquid xenon TPCs suitable for studying more complex event topologies. Such multi-site events are important for the study of positron-emitting double-weak decays [3].

2.3 New Calibration Sources for Double-Weak Decay Searches

Besides dark matter searches, large liquid xenon detectors are also sensitive to several rare double-weak decay processes of xenon isotopes. One especially interesting process is the two-neutrino electron-capture with positron emission ($2\nu EC\beta^+$) decay of ^{124}Xe :

$$^{124}\text{Xe} + e^- \rightarrow ^{124}\text{Te} + e^+ + 2\nu_e + X_K \quad (1)$$

Here, X_K denotes the atomic de-excitation energy released after K-shell capture.

The $2\nu EC\beta^+$ decay of ^{124}Xe has not yet been observed, and its half-life has therefore not been measured. A measurement would provide an additional test of nuclear matrix element calculations for double-beta decay. The corresponding neutrinoless mode, $0\nu EC\beta^+$, would violate lepton-number conservation and could provide information about the Majorana nature and effective mass of neutrinos [3].

In this decay, an atomic electron is captured by the nucleus, while a positron and two neutrinos are emitted. The electron is most likely captured from the inner K-shell, although

capture from higher atomic shells is also possible. The capture leaves a vacancy in the atomic shell. Electrons from higher shells move down to fill this vacancy and emit characteristic X-rays and Auger-Meitner electrons in the process.

The emitted positron deposits its kinetic energy through excitation and ionization of the xenon before annihilating with an electron. During the annihilation, two gamma rays with an energy of 511 keV are produced and emitted in opposite directions.

$$e^+ + e^- \rightarrow 2\gamma_{511 \text{ keV}} \quad (2)$$

This decay creates a characteristic multi-site event topology inside the detector. The X-rays and Auger-Meitner electrons produced during the atomic shell rearrangement deposit their energy close to the decay site and are therefore typically reconstructed as a single energy deposition. Further energy depositions are produced by the positron and the two annihilation gamma rays. The characteristic topology of this decay is shown in Figure 2. Such events are more complex than the low-energy single-site events usually expected from dark matter interactions. Good event reconstruction and precise detector calibration are therefore important for identifying these event topologies [3].

The increasing size of future liquid xenon detectors creates new challenges for detector calibration. In large detectors, external calibration sources can no longer efficiently reach the inner detector regions because of the strong self-shielding of liquid xenon due to its high density. Most of the radiation from external sources is absorbed in the outer detector regions before reaching the centre of the detector [2, 3].

For this reason, internal radioactive calibration sources are an interesting alternative. Since they can be distributed throughout the xenon volume, they allow for detector studies over the full detector volume. This makes it possible to investigate effects such as charge diffusion, spatial reconstruction, and cluster identification [3].

The radioactive isotope ^{79}Kr is a promising candidate for such an internal calibration source. Since ^{79}Kr is a noble gas, it can be mixed with xenon and distributed throughout the detector volume.

^{79}Kr has a half-life of about 35 hours and decays mainly by electron capture, with a smaller positron-emission branch, as shown in Figure 3. In contrast to the $^{124}\text{Xe } 2\nu\text{EC}\beta^+$ decay, these are separate decay branches and do not occur together in the same event.

Electron capture produces X-rays and Auger-Meitner electrons, while positron emission produces a positron followed by two 511 keV annihilation gamma rays. Both branches can also populate excited states of ^{79}Br , which de-excite by gamma emission. The different branches therefore provide several signal components useful for studying multi-site event reconstruction [3, 11].

2.4 Scope of this Work

The aim of the wider project is to develop and test ^{79}Kr as a new internal calibration source for liquid xenon detectors. The source is produced at the Paul Scherrer Institute (PSI) by irradiating potassium bromide (KBr) with a proton beam. The ^{79}Kr is produced through proton-induced reactions on bromine and is then extracted in gaseous form.

The radioactive krypton is transported to the University of Zurich in a so-called cold trap. The cold trap consists of a U-shaped copper tube that is cooled to retain the krypton. While the trap is cold, other gases are removed by vacuum pumping. At the destination, the trap is warmed to release the krypton into the xenon gas system.

The ^{79}Kr source is intended to be tested in a small-scale xenon TPC at the University of Zurich. Before these measurements, the source handling and injection procedure will first be

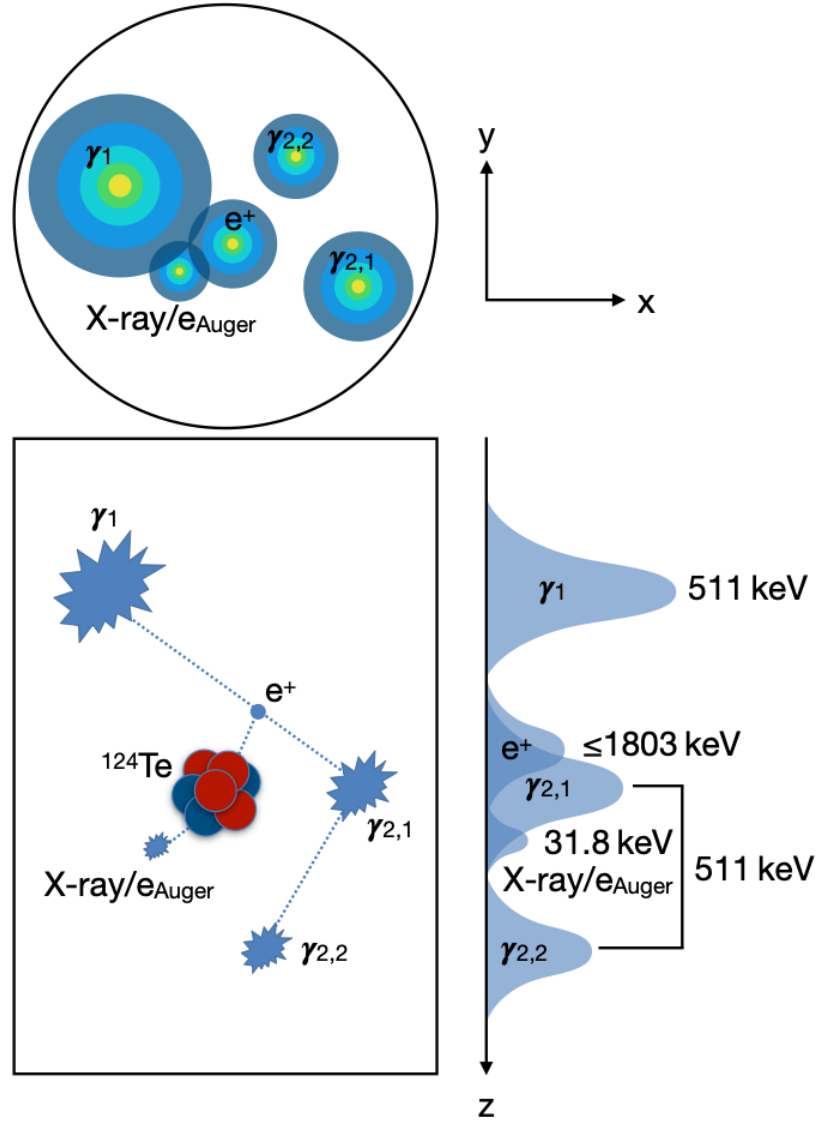


Figure 2: Schematic topology of the $2\nu EC\beta^+$ decay of ^{124}Xe inside a liquid xenon detector. The positron annihilates into two 511 keV gamma rays while additional X-rays and Auger-Meitner electrons are produced close to the decay site. The different energy depositions can create several separated interaction clusters inside the detector. Figure from [3].

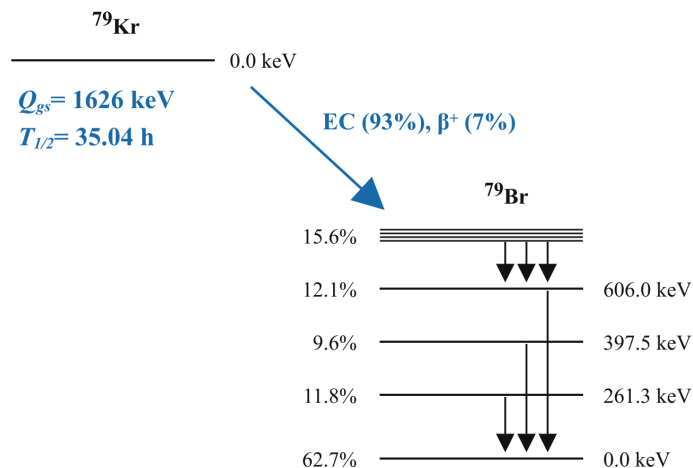


Figure 3: Simplified decay scheme of ^{79}Kr . The isotope decays predominantly by electron capture (EC), with a smaller positron-emission (β^+) branch. The percentages on the left indicate the total feeding intensities of the ^{79}Br levels. The closely spaced lines represent higher excited states that are not shown individually. The excited states subsequently de-excite towards the stable ground state by gamma emission and internal conversion. Figure created for this work. Numerical values are taken from [11].

tested using a simpler detector filled with gaseous xenon. For this purpose, a cross-shaped detector with two opposing PMTs is used. In the following, this setup is referred to as the cross detector. Both PMTs observe the same xenon gas volume and can detect the scintillation light produced by energy depositions from ^{79}Kr decays.

The scintillation light is expected to result mainly from energy deposited in the xenon by X-rays and Auger-Meitner electrons following electron capture, as well as by emitted positrons. In addition, external NaI detectors are used to detect gamma rays leaving the cross detector. These include the 511 keV annihilation gamma rays from positron emission and gamma rays from excited states of ^{79}Br , as shown in Figure 3.

This thesis focuses on the preparation of the cross detector for these future measurements. The PMTs used in the detector are characterized with respect to their gain and afterpulse behaviour. Based on these measurements, two PMTs are selected for the detector. The cross detector is then assembled and integrated into the existing gaseous xenon circulation system at the University of Zurich.

3 Photomultiplier Tubes

For the detection of low-intensity signals, photomultiplier tubes can be used. A photomultiplier is a highly sensitive device capable of converting incident photons into measurable electrical signals.

The general operating principle is shown in Figure 4. When a photon hits the photocathode, a photoelectron can be emitted via the photoelectric effect. This electron is accelerated toward the first dynode by an applied high voltage. Upon impact, secondary electrons are released and subsequently accelerated toward the next dynode. This multiplication process is repeated over several dynodes, increasing the number of electrons at each step. The resulting group of electrons is then collected at the anode, where it is converted into a measurable electrical signal.

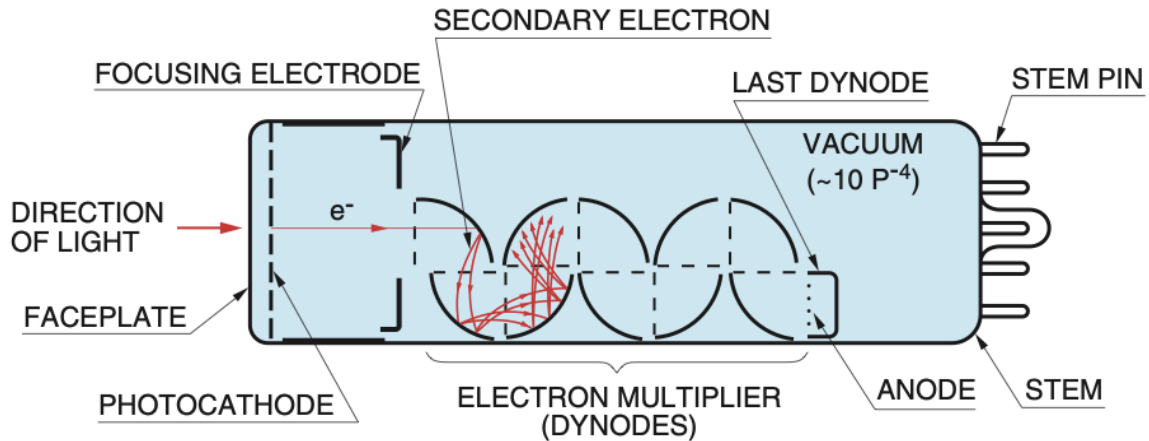


Figure 4: Schematic of a photomultiplier tube. Photoelectrons emitted at the photocathode are multiplied through successive dynodes and collected at the anode, generating an electrical signal. Figure from [13].

[12].

3.1 Quantum Efficiency

The quantum efficiency (QE) describes how likely it is that an incoming photon produces a photoelectron at the photocathode of the PMT. It is defined as the ratio between the number of emitted photoelectrons and the number of incident photons. A higher quantum efficiency means that more of the incoming light can be detected by the PMT [14].

The quantum efficiency depends on the photocathode material and also on the wavelength of the incoming light. This is especially important for liquid xenon detectors because xenon scintillation light is emitted in the vacuum ultraviolet (VUV) region around 175 nm [15]. PMTs used in xenon detectors therefore need to have a good sensitivity at this wavelength [7, 13]. PMTs with higher quantum efficiency are generally preferred because they can detect more scintillation light and therefore improve the detector performance [13].

3.2 PMT Gain

The gain of a photomultiplier tube describes the amplification of the initial photoelectron signal. It is defined as the average number of electrons collected at the anode for one photoelectron emitted from the photocathode. The gain mainly depends on the applied high voltage and the dynode structure of the PMT. In general, a higher voltage leads to a larger amplification of the signal. Stable high-voltage settings are therefore important for a stable detector response and reliable measurements [13].

The PMT gain is related to the charge of a single-photoelectron (SPE) signal by

$$G = \frac{Q_{\text{SPE}}}{e}, \quad (3)$$

where G is the PMT gain, Q_{SPE} is the average charge corresponding to a single-photoelectron, and e is the elementary charge.

The gain of a PMT is usually measured using triggered single-photon signals from an LED. The light intensity is kept low so that only a small number of photons reach the photocathode for each LED pulse. The recorded PMT signals can then be integrated to obtain a charge spectrum. Events without a detected photoelectron form the noise pedestal, while events with detected photoelectrons contribute at larger integrated charge values. The position of the single-photoelectron contribution relative to the pedestal is directly related to the PMT gain.

Figure 5 shows an example of an integrated charge spectrum recorded with one of the PMTs tested in this work at an applied high voltage of 800 V. The analogue voltage signal produced by the PMT is converted into discrete numerical values by the analogue-to-digital converter (ADC) of the digitizer. These ADC values represent the measured signal amplitude at each sampling point of the waveform. By integrating the baseline-subtracted ADC values over the pulse region, an integrated ADC area proportional to the charge of the PMT pulse is obtained.

The large peak around zero integrated ADC area corresponds to the pedestal, where no photoelectron signal was detected. The broader contribution at larger integrated ADC areas contains signals from detected photoelectrons. The first photoelectron contribution corresponds to the single-photoelectron (SPE) signal and is used to determine the average charge produced by one detected photoelectron.

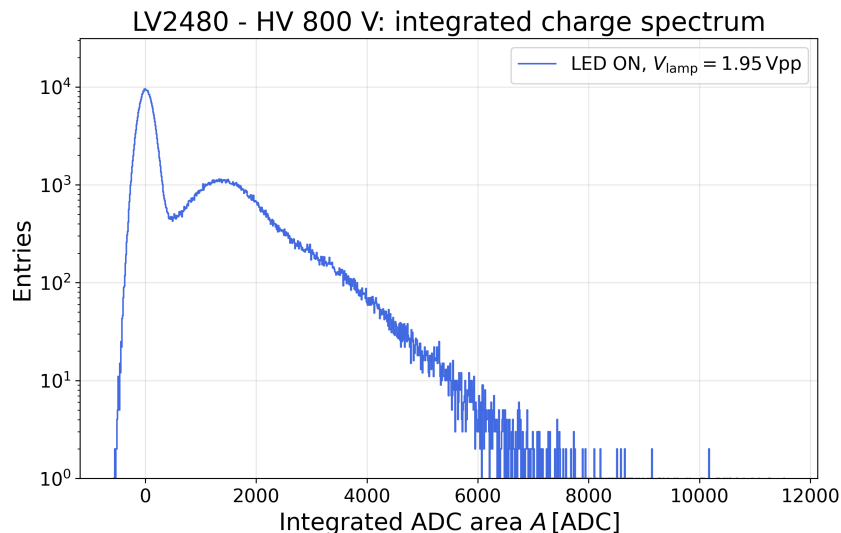


Figure 5: Integrated charge spectrum recorded with one of the PMTs tested in this work at an applied high voltage of 800 V. The large peak around zero integrated ADC area corresponds to the pedestal, while the broader distribution at larger values contains the photoelectron signals.

Different methods can be used to determine the SPE charge from the measured charge spectrum. In this work, a model-independent and a model-dependent method were used.

The model-independent method determines the average SPE charge from the average measured charge and the average number of detected photoelectrons. It does not require a model for the shape of the charge spectrum and can therefore also be used when the individual photoelectron contributions are not clearly separated. The average number of detected photoelectrons is determined from the fraction of events without a detected photoelectron.

The model-dependent method instead fits the measured charge spectrum with a model describing the pedestal and the different photoelectron contributions. The gain is determined from the separation between the pedestal position and the first photoelectron contribution. In addition to the gain, the fit provides information about the width of the SPE distribution, which can be used to characterize the single-photoelectron resolution of the PMT.

The detailed implementation of both methods and the corresponding gain analysis are described in Section 4.2.

3.3 Afterpulses

Afterpulses are delayed signals that appear some time after the main PMT pulse. They are mainly caused by small amounts of residual gas inside the PMT vacuum tube. During the electron multiplication process, electrons travelling through the dynode structure can ionize gas molecules inside the PMT. The resulting positive ions are accelerated back towards the photocathode or the dynodes by the electric field inside the tube. When these ions hit the photocathode or dynodes, additional electrons can be released and produce delayed secondary pulses, called afterpulses [13, 16].

The delay time of the afterpulses depends on the type of ion and on the electric field configuration inside the PMT. Heavier ions move more slowly and therefore produce signals at larger delay times. Because of this, the afterpulse timing spectrum can provide information about the residual gases present inside the PMT vacuum.

Although PMTs operate under high vacuum conditions, small contaminations or tiny vacuum leaks can still lead to increased afterpulse rates. In particular, increasing afterpulse contributions associated with xenon or argon ions can indicate vacuum degradation or small leaks. Thermal stress during cooling and warming of the PMTs can increase the risk of such leaks. This is especially important for liquid xenon detectors, where the PMTs are operated at cryogenic temperatures close to 178 K for long periods of time.

In liquid xenon detectors, very small light signals often have to be detected close to the single-photoelectron level. Since afterpulses are connected to the original PMT signal, they can create additional background signals and affect the detector response. Large afterpulse rates can worsen the energy resolution, influence timing measurements, and make the reconstruction of small signals more difficult. In extreme cases, they can also lead to unstable PMT operation or additional light emission effects [16].

For low-background experiments, PMTs with low afterpulse rates are therefore preferred.

3.4 Dark Counts

Dark counts are signals produced by the PMT even when no light is entering the detector. The main source of dark counts is thermionic emission from the photocathode and dynodes. Additional contributions can come from radioactive decays, leakage currents, or electrical field effects inside the PMT [13].

The dark-count rate depends on several factors, such as temperature, applied high voltage, and the PMT material itself. In general, lower temperatures reduce thermionic emission and therefore also reduce the dark-count rate. This is important for liquid xenon detectors, which are operated at cryogenic temperatures [17].

In low-background experiments, dark counts are important because they contribute to the detector noise and can limit the sensitivity for very small signals. Since PMTs in liquid xenon detectors often operate close to the single-photoelectron level, dark counts can affect signal identification and trigger performance. PMTs with lower dark-count rates are therefore preferred for rare-event searches [7, 13].

3.5 Hamamatsu R8520 PMT

The PMTs used in this work were Hamamatsu R8520-406 photomultiplier tubes, one of which is shown in Figure 6. These are compact one-inch square PMTs developed for low-background

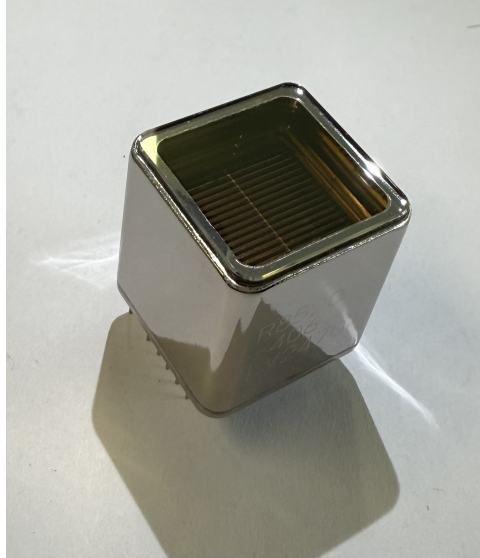


Figure 6: Hamamatsu R8520-406-001 one-inch square photomultiplier tube used in this work.

applications and for the detection of xenon scintillation light in the vacuum ultraviolet region. The R8520 PMTs can be operated at cryogenic temperatures around -100°C and are therefore suitable for use in liquid xenon environments [7, 18].

The PMTs use a bialkali photocathode together with a metal-channel dynode structure consisting of ten dynode stages. They are operated with negative high voltage and reach a typical gain of about 10^6 at an operating voltage around 800 V according to the datasheet. The synthetic silica window allows for efficient detection of xenon scintillation light at wavelengths around 175 nm [18].

The schematic shown in Figure 4 illustrates the general working principle of a photomultiplier tube. In contrast to the simplified dynode chain shown there, the R8520 uses a metal-channel dynode structure. In this design, the electrons are guided and multiplied inside small metal channels instead of travelling between larger open dynodes [13].

The internal geometry of the R8520 also influences the afterpulse behaviour of the PMT. In particular, the shape of the PMT determines the electric field lines between the photocathode and the first dynode and therefore affects the motion of positive ions inside the tube. As a result, the relation between afterpulse delay times and specific residual gas ions depends on the internal PMT geometry and cannot be directly transferred between different PMT designs [13, 19].

The metal-channel dynode structure provides a short and well-defined electron transit path through the PMT. This typically results in only a small variation in the electron transit time, referred to as the transit-time spread, and therefore in good time resolution. At the same time, fluctuations in the electron multiplication process can lead to broader single-photoelectron charge distributions. A simplified illustration of the metal-channel structure is shown in Figure 7.

Figure 8b shows the spectral response and quantum efficiency of the PMT as a function of wavelength. The PMT has its highest sensitivity in the VUV region around the xenon scintillation wavelength, with a typical quantum efficiency of about 30% [18].

Figure 8a shows the typical gain behaviour as a function of the applied supply voltage. The gain increases with increasing voltage and reaches values around 10^6 near 800 V [18].

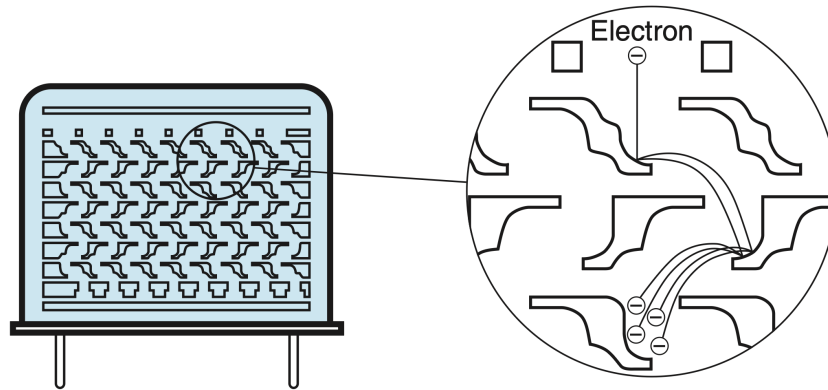
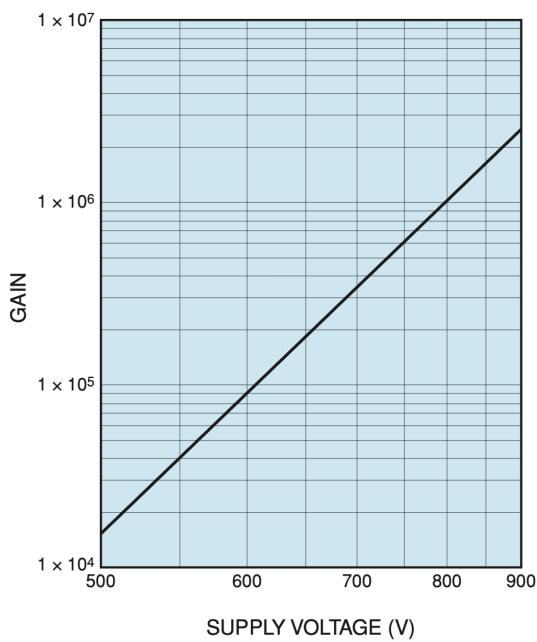
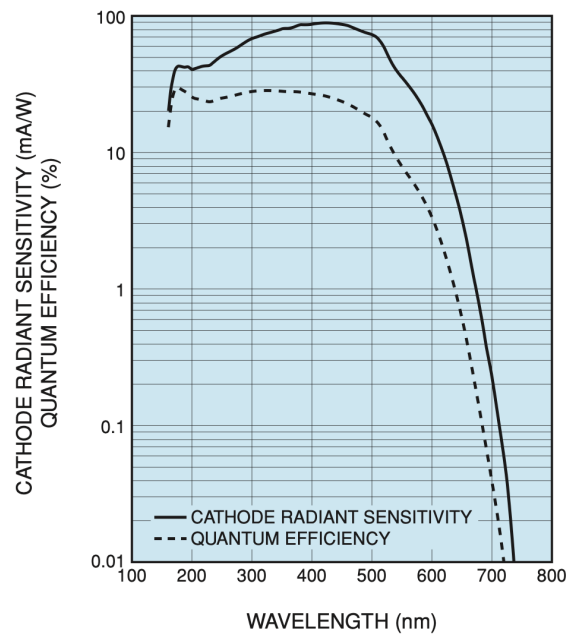


Figure 7: Simplified illustration of the metal-channel dynode structure used in the Hamamatsu R8520 PMT. Electrons are guided and multiplied inside small metal channels during the amplification process. Figure from [13].



(a) Typical gain as a function of the applied supply voltage.



(b) Typical spectral response and quantum efficiency as a function of wavelength.

Figure 8: Typical gain and spectral response of the Hamamatsu R8520-406 PMT. Figures from [18].

Part II

PMT Characterization

The second part of this thesis focuses on the characterization of the photomultiplier tubes (PMTs). At the beginning of this study, ten Hamamatsu R8520 PMTs were available. The manufacturer test values for these PMTs are summarized in Table 1.

The cathode luminous sensitivity S_{cathode} describes the photocathode current produced per unit of incident luminous flux. The anode luminous sensitivity S_{anode} describes the corresponding anode current per unit of incident luminous flux and therefore also includes the electron multiplication in the PMT. The anode dark current I_{dark} is the current measured at the anode in the absence of light. The blue sensitivity index provides a measure of the photocathode sensitivity in the blue wavelength region. In addition to these quantities, the table includes the gain at 800 V reported by Hamamatsu.

Based on these values, four PMTs were selected for further characterization. These four PMTs were then investigated in more detail using gain and afterpulse measurements. Based on the results of these measurements, two PMTs were selected for use in the cross detector.

PMT	S_{cathode} [$\mu\text{A}/\text{lm}$]	Blue sens. index	S_{anode} [A/lm]	I_{dark} [nA]	$G_{\text{Hamamatsu}}$
LV2465	106	11.0	115	0.08	1.1×10^6
LV2468	112	11.6	191	0.13	1.7×10^6
LV2469	105	11.6	291	0.10	2.8×10^6
LV2470	104	10.9	84	0.06	0.8×10^6
LV2471	106	11.1	95	0.05	0.9×10^6
LV2478	122	12.1	142	0.17	1.2×10^6
LV2480	115	12.3	465	0.24	4.1×10^6
LV2481	130	12.7	428	0.32	3.3×10^6
LV2483	115	12.2	421	0.17	3.7×10^6
LV2485	85	10.7	326	0.27	3.8×10^6

Table 1: Manufacturer test values provided by Hamamatsu for the ten available R8520-406 photomultiplier tubes. The anode luminous sensitivity, anode dark current, and gain values were measured at an operating voltage of 800 V. The four PMTs selected for further characterization are highlighted in bold.

4 Experimental Methods

4.1 Experimental Setup

A schematic overview of the PMT testing setup used for the gain and afterpulse measurements is shown in Figure 9. The measurements were performed inside the Sand-Box setup, which provided a dark environment for the measurements and was therefore well suited for PMT testing and characterization.

The PMTs were equipped with newly designed compact voltage-divider bases. The printed circuit boards contain a resistive divider chain that distributes the applied high voltage over the photocathode and dynode stages. Capacitors are included at the last dynode stages to stabilize the voltages during signal formation. The amplified electron signal is collected at the anode and read out through the signal connection of the base. The bases were mounted directly behind

PMT-Testing Set-up

University of Zurich

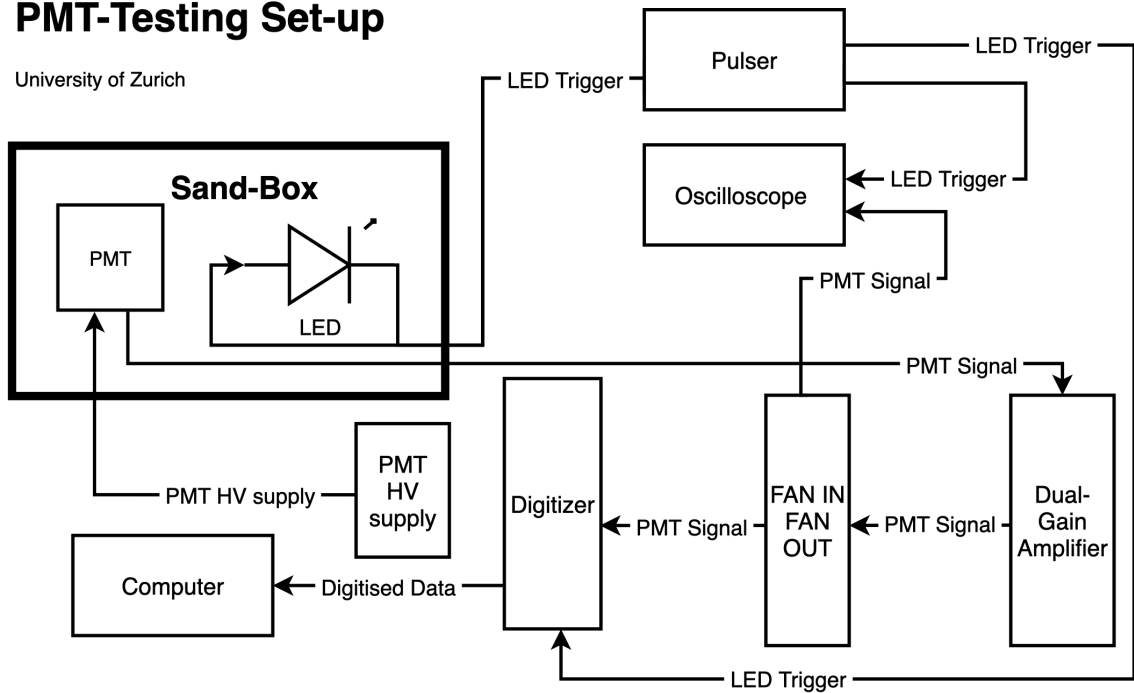


Figure 9: Schematic overview of the PMT testing setup used for the gain and afterpulse measurements. The PMT signal was amplified using a dual-gain amplifier and distributed to the oscilloscope and digitizer through a FAN IN/FAN OUT module. The recorded waveforms were transferred to a local computer for further analysis.

the PMTs and connected to the high-voltage supply and signal readout, as shown in Figure 10. Their compact design made them suitable for the limited space in the cross detector.

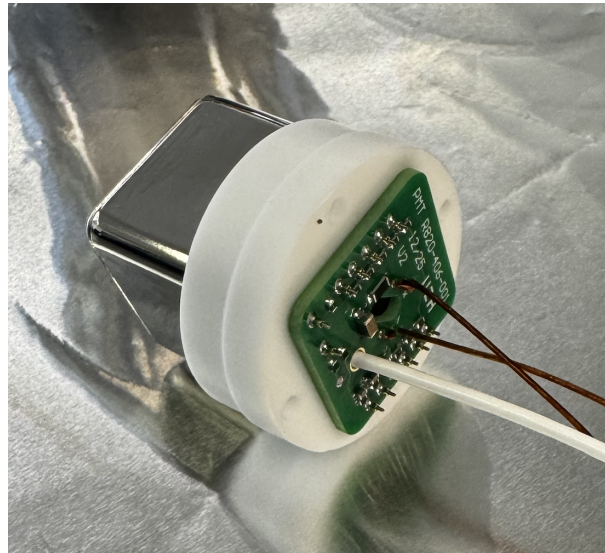


Figure 10: Hamamatsu R8520 PMT equipped with the redesigned voltage-divider base. The compact printed circuit board is mounted directly behind the PMT and connected to the high-voltage and signal cables. The PMT is held in a custom white PTFE support structure.

For the measurements, an LED with a wavelength of 470, nm, triggered by a pulse generator, was used as the light source. The pulser was operated with a pulse width of 30, ns, including a

rise time of 5, ns and a fall time of 5, ns. The same trigger signal from the pulser was also sent to the oscilloscope and the digitizer. In this way, the LED pulse and the recorded waveform were synchronized.

The PMT signal was first amplified using a dual-gain amplifier with an amplification factor of 10 in order to make small signals easier to detect. Afterwards, the signal was sent to a FAN IN/FAN OUT module, which distributed the signal simultaneously to both the oscilloscope and the digitizer.

The waveforms were recorded with a CAEN V1730D digitizer. The digitizer has a 14-bit ADC resolution and was operated with a sampling frequency of 500 MHz, corresponding to one sample every 2 ns. The digitizer was operated with a 2.0 V full-scale input range and a 50 Ω input impedance. These parameters were later used to convert the integrated ADC area into units of elementary charge.

The oscilloscope was used mainly to monitor the signals during the measurements and to check the shape, height, and stability of the pulse. The digitizer recorded the waveforms and transferred the data to a local computer, where further analysis was performed. Figures 11 and 12 show photographs of the Sand-Box and the electronics setup used during the measurements.

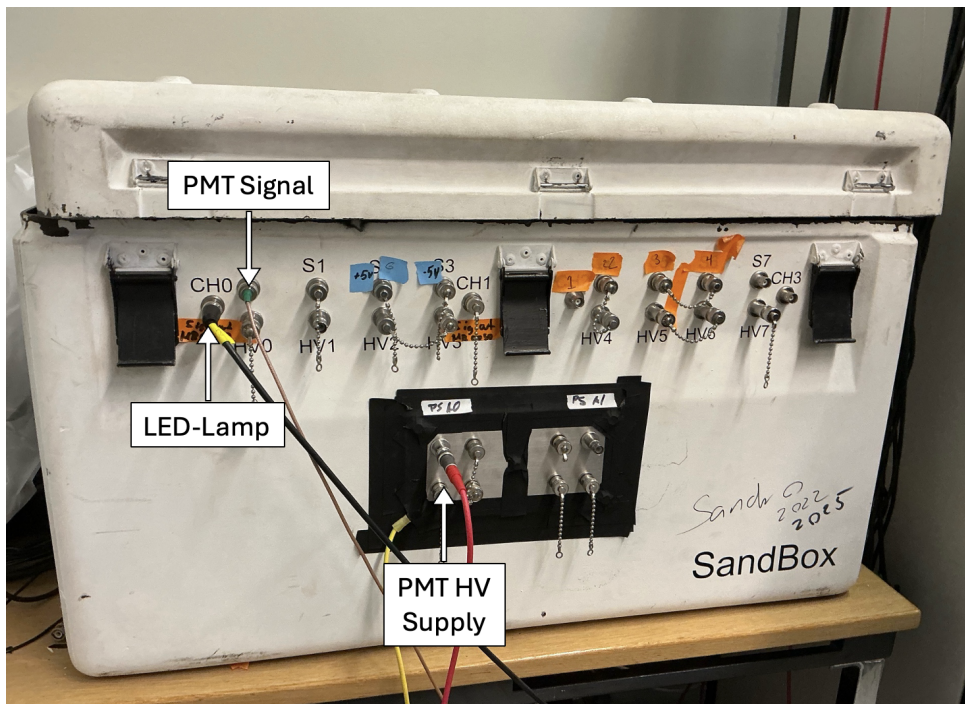


Figure 11: Sand-Box setup used for the PMT characterization measurements. The setup provided a dark environment for the measurements.

The setup used for the gain and afterpulse measurements was mostly the same. The main difference between the two measurements was the operating voltage of the LED, which determines the average number of photons produced per trigger.

For the gain measurements, a high-voltage scan was performed, meaning that the PMT was measured at different operating voltages while keeping the LED settings fixed. The measurements were carried out between 700 V and 900 V in steps of 50 V. At each voltage, 500 000 waveforms were recorded.

The LED voltage was adjusted such that only about one in ten LED pulses produced a detectable PMT signal. The measurements were therefore performed at the single-photoelectron level, corresponding to an occupancy of approximately 10%, where the occupancy denotes the

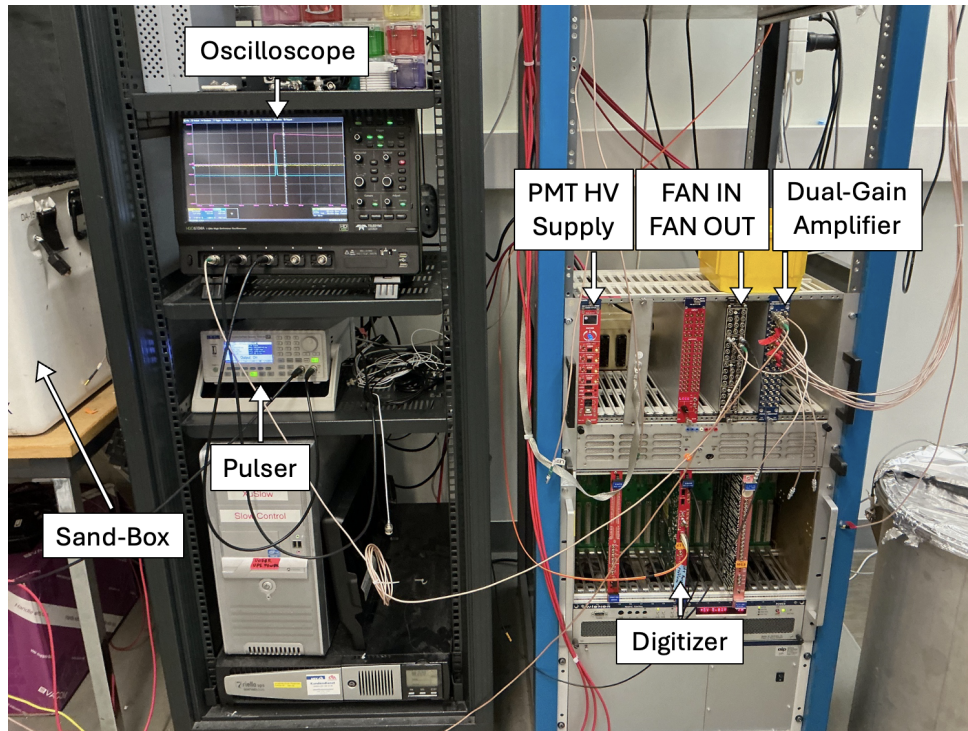


Figure 12: Electronics setup used for the PMT characterization measurements, including the oscilloscope, pulser, digitizer, and amplifier modules.

probability that an LED pulse produces a detectable PMT signal. This low occupancy is well suited for the model-dependent gain calculation because the single-photoelectron peak can be separated more clearly from higher photoelectron contributions.

For the model-independent method, a higher occupancy of around two photoelectrons would normally be preferred. However, since the model-dependent method was used as the main method in this analysis, the LED settings were chosen mainly for this method. The model-independent method was still used as a cross-check and also to provide starting values for the fit.

The LED voltages were kept as similar as possible between the PMTs, but small adjustments were necessary because the LED output was not always exactly the same between measurements. The resulting LED settings used for the gain and afterpulse measurements are summarized in Table 2.

PMT	Gain LED voltage	Afterpulse LED voltage
LV2480	1.90 V _{pp}	2.15 V _{pp}
LV2481	1.95 V _{pp}	2.15 V _{pp}
LV2483	1.95 V _{pp}	2.15 V _{pp}
LV2485	1.95 V _{pp}	2.10 V _{pp}

Table 2: LED lamp settings used for the gain and afterpulse measurements of the four characterized PMTs. For each PMT, the same gain LED setting was used for all operating voltages between 700 V and 900 V.

For the afterpulse measurements, a higher occupancy was required than for the gain measurements. Since afterpulses appear as delayed secondary pulses following the main PMT signal, a larger number of primary photoelectrons was needed in order to observe enough afterpulse events for the analysis. For this reason, the LED voltage was increased such that the main pulse

height on the oscilloscope was around 500 mV to 700 mV, which corresponds to roughly 10 PE per trigger. The corresponding LED settings are listed in Table 2. For each PMT, 500 000 waveforms were recorded for the afterpulse measurement.

4.2 Gain Analysis

The PMT gain analysis used in this work was based on the Python package `pmt_analysis`, mainly developed by Alexander Bismarck [20]. The original implementation already provided a model-independent gain calculation. During this thesis, the analysis code was extended to also include a model-dependent fit of the charge spectrum, automatic processing of several data sets, goodness-of-fit tests, residual plots, and automatic saving of the numerical results. The extended analysis code is available in the corresponding GitHub repository [21].

Two different methods were used to determine the PMT gain. The model-independent method determines the gain from the average measured charge and the average number of detected photoelectrons without fitting the full charge spectrum. The model-dependent method instead determines the gain from a fit to the pedestal and photoelectron peaks of the measured charge spectrum. Both methods are described in the following sections.

4.2.1 Waveform Integration

The LED was operated in triggered mode. Each LED pulse also triggered the recording of one PMT waveform with the digitizer. In the following analysis, each recorded waveform is therefore referred to as one trigger.

For each recorded waveform, the baseline B was determined from the median value of the first 100 ADC samples. This region corresponds to the part of the waveform before the PMT pulse appears and is used to estimate the electronic offset of the digitizer. The baseline window was therefore defined as the first 100 samples of the waveform, while the remaining samples were used as the signal integration window W_{sig} . With the sampling frequency of 500 MHz, one ADC sample corresponds to 2 ns. The baseline window therefore covers the first 200 ns of each waveform.

Figure 13 shows a typical raw single-photoelectron waveform recorded with the CAEN V1730D digitizer. The PMT signal appears as a negative pulse on top of the ADC baseline. The shaded region marks the first 100 samples used for the baseline calculation. Since the PMT pulses are negative in the raw waveform, the traces were baseline-subtracted and sign-inverted according to

$$a_i = -(x_i - B), \quad (4)$$

where x_i is the raw ADC value of sample i and a_i is the processed waveform amplitude.

The effect of this processing step is shown in Figure 14. The integrated ADC area was then calculated in the fixed signal window W_{sig} as

$$A = \sum_{i \in W_{\text{sig}}} a_i, \quad (5)$$

where W_{sig} denotes the signal integration window defined above. Using the definition of a_i , this can also be written as

$$A = N_{\text{sig}} B - \sum_{i \in W_{\text{sig}}} x_i, \quad (6)$$

where N_{sig} is the number of samples inside the integration window.

The integrated ADC area was converted into units of elementary charge using

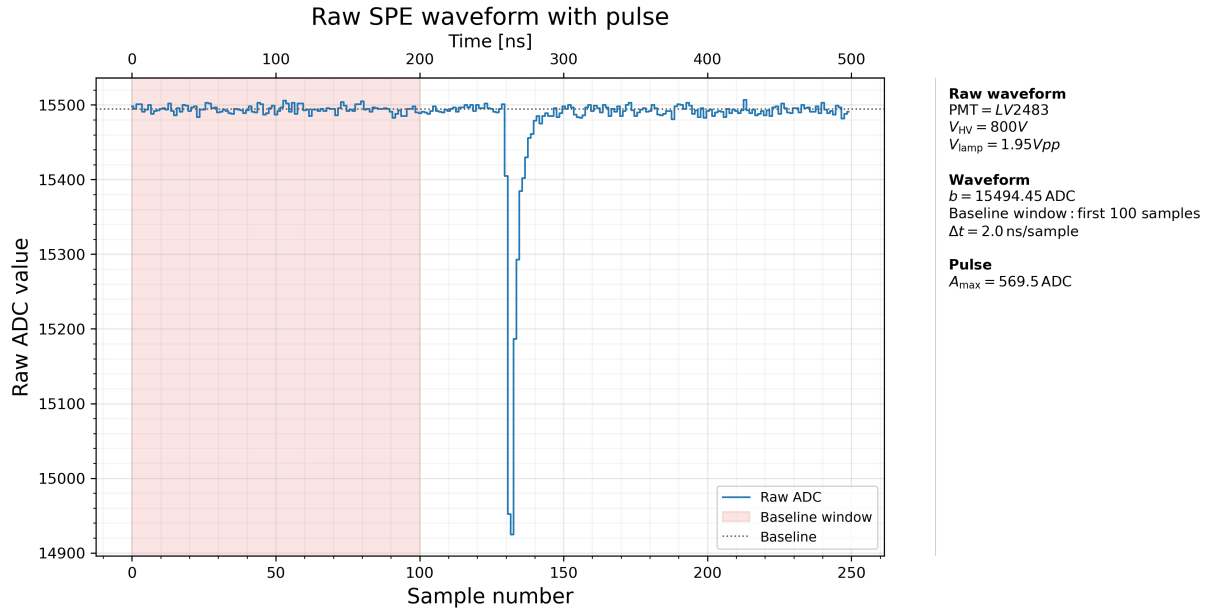


Figure 13: Example of a raw SPE waveform recorded with PMT LV2483 at an applied high voltage of 800 V. The PMT signal appears as a negative pulse in the ADC trace. The shaded region indicates the first 100 samples used for the baseline determination.

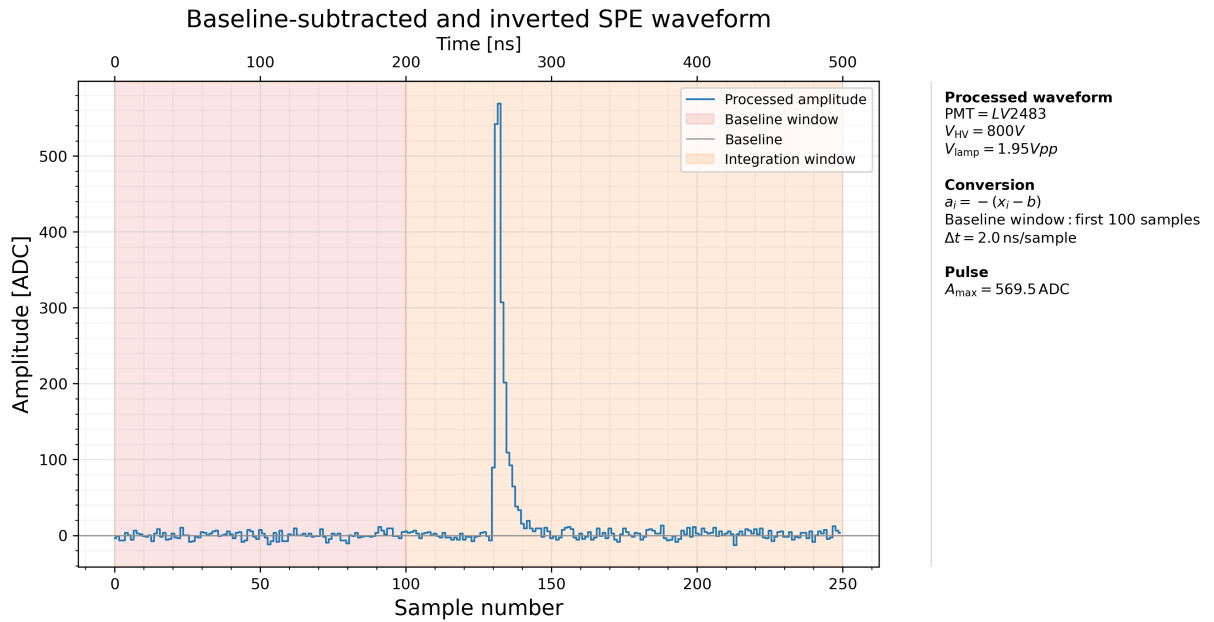


Figure 14: The same SPE waveform after baseline subtraction and sign inversion. The PMT pulse now appears as a positive signal. The orange shaded region indicates the fixed signal integration window W_{sig} used to calculate the integrated ADC area.

$$c_{\text{ADC} \rightarrow e} = \frac{r_{\text{ADC}}}{f_{\text{ADC}} Z_{\text{ADC}} a_{\text{ADC}} e}. \quad (7)$$

Here, r_{ADC} is the voltage range per ADC count, f_{ADC} is the sampling frequency, Z_{ADC} is the input impedance of the digitizer, a_{ADC} is the amplification factor of the readout electronics, and e is the elementary charge.

For the 14-bit CAEN V1730D digitizer with a full-scale input range of 2.0 V, the voltage range per ADC count is

$$r_{\text{ADC}} = \frac{2.0 \text{ V}}{2^{14}}. \quad (8)$$

Substituting $r_{\text{ADC}} = 2.0 \text{ V}/2^{14}$, $f_{\text{ADC}} = 500 \text{ MHz}$, $Z_{\text{ADC}} = 50 \Omega$, $a_{\text{ADC}} = 10$, and $e = 1.602 \times 10^{-19} \text{ C}$ into Eq. (7) gives

$$c_{\text{ADC} \rightarrow e} = \frac{(2.0 \text{ V}/2^{14})}{(500 \times 10^6 \text{ s}^{-1}) \times 50 \Omega \times 10 \times (1.602 \times 10^{-19} \text{ C})} \simeq 3.05 \times 10^3 \frac{e^-}{\text{ADC area unit}}. \quad (9)$$

4.2.2 Model-Independent Gain Calculation

The first gain estimate was obtained using the model-independent method from [22]. In this approach, the PMT gain is determined from the average charge measured per trigger together with the average number of detected photoelectrons. The method does not rely on fitting the full charge spectrum and is therefore referred to as model-independent.

In the analysis, the average number of detected photoelectrons per LED trigger is described by the occupancy λ . Assuming Poisson statistics, the probability of observing zero photoelectrons is

$$P(0) = e^{-\lambda}. \quad (10)$$

To estimate this probability, the analysis code scans different charge thresholds A_{thr} in the pedestal region of the charge spectrum. For each threshold, the number of LED-on events below the threshold was compared to the normalized number of LED-off events below the same threshold. The resulting occupancy values were then smoothed in order to reduce statistical fluctuations. The final threshold was chosen from the stable occupancy region by requiring a sufficiently small relative occupancy uncertainty.

By comparing the fraction of such events in the LED-on and LED-off spectra, the occupancy can be estimated as

$$\lambda = -\ln \left(\frac{n_{\text{on}}(A < A_{\text{thr}})}{\tilde{n}_{\text{off}}(A < A_{\text{thr}})} \right), \quad (11)$$

where n_{on} is the number of LED-on events below the threshold and $\tilde{n}_{\text{off}}$ is the normalized number of LED-off events below the same threshold. The LED-off distribution was normalized to the total number of LED-on events in order to account for different sample sizes.

The average single-photoelectron charge was then determined from the difference between the mean LED-on and LED-off charge distributions

$$\bar{\psi} = \frac{\langle A_{\text{on}} \rangle - \langle A_{\text{off}} \rangle}{\lambda}. \quad (12)$$

The model-independent gain is therefore

$$G_{\text{MI}} = \bar{\psi} \cdot c_{\text{ADC} \rightarrow e}. \quad (13)$$

The uncertainty of the model-independent gain was determined from the uncertainties of the charge moments and of the occupancy estimate. The statistical contribution originates from the finite number of recorded LED-on and LED-off waveforms and from the widths of the integrated charge distributions. In addition, the occupancy λ has an uncertainty because it is determined from the number of events below the selected pedestal threshold. The different uncertainty contributions were combined in quadrature,

$$\sigma_{\bar{\psi}} = \sqrt{\sigma_{\bar{\psi},\text{stat}}^2 + \sigma_{\bar{\psi},\lambda}^2}. \quad (14)$$

The uncertainty of the model-independent gain was then obtained as

$$\sigma_{G_{\text{MI}}} = \sigma_{\bar{\psi}} \cdot c_{\text{ADC} \rightarrow e}. \quad (15)$$

The model-independent result was mainly used as a cross-check of the model-dependent fit and as a starting value for the fit initialization.

4.2.3 Model-Dependent Gain Calculation

The second gain estimate was obtained using the model-dependent method. In contrast to the model-independent approach, this method uses the shape of the full integrated charge spectrum. The pedestal and the individual photoelectron contributions are described by an analytical model, and the gain is determined from the separation between the pedestal and the single-photoelectron peak. [23]

For the model-dependent analysis, the LED-on integrated charge spectrum was fitted with a constrained multi-photoelectron model. As a first step, the pedestal position and width were estimated from the LED-off spectrum. The maximum of the LED-off histogram was identified, and a Gaussian function was fitted in a region around this maximum,

$$G_0(A) = A_0 \exp \left[-\frac{1}{2} \left(\frac{A - \mu_0}{\sigma_0} \right)^2 \right], \quad (16)$$

where A_0 is the amplitude of the Gaussian, μ_0 is the pedestal mean, and σ_0 is the pedestal width. The fit was weighted with the statistical uncertainty of each histogram bin, approximated by $\sqrt{N_i}$.

The full LED-on spectrum was then fitted with a model consisting of the pedestal contribution and several photoelectron peaks. The pedestal region can show an asymmetric tail towards larger integrated charges. This can originate from small signals that are not clearly separated from the pedestal, for example from electronic fluctuations or very small PMT pulses. To account for this asymmetric contribution, the pedestal was modeled as a combination of a Gaussian and an exponentially modified Gaussian (EMG),

$$P_0(A) = (1 - w) G_0(A) + w E_0(A), \quad (17)$$

where w is the fitted tail fraction and $E_0(A)$ is the EMG component. The parameter w was constrained between zero and a maximum value in order to prevent the tail component from dominating the pedestal description. The photoelectron contribution was modeled as a sum of Gaussian peaks. The peak positions were constrained to be equally spaced,

$$\mu_i = \mu_0 + i\Delta\mu, \quad (18)$$

where i is the photoelectron number and $\Delta\mu$ is the separation between neighboring photoelectron peaks. The peak widths were constrained according to

$$\sigma_i = \sqrt{i} \sigma_1, \quad (19)$$

which describes the increasing width of the charge distribution with increasing photoelectron number. The amplitudes of the photoelectron peaks were constrained by Poisson statistics. The amplitude of the i -photoelectron contribution was written as

$$H_i = A_{\text{PE}} \frac{\lambda_{\text{fit}}^i}{i!}, \quad (20)$$

where λ_{fit} is the fitted occupancy and A_{PE} is an overall normalization parameter. The common exponential factor of the Poisson distribution is absorbed into the normalization. Peaks up to six photoelectrons were included in the fit. The full model used for the LED-on spectrum was therefore

$$F(A) = (1 - w) G_0(A) + w E_0(A) + \sum_{i=1}^6 H_i \exp \left[-\frac{1}{2} \left(\frac{A - \mu_i}{\sigma_i} \right)^2 \right]. \quad (21)$$

In this model, the pedestal describes events without a detected photoelectron, while the peaks at higher integrated charge correspond to one or more detected photoelectrons. The separation between neighboring photoelectron peaks therefore represents the average charge produced by a single-photoelectron.

The model-independent gain estimate was used as an initial estimate for the peak spacing $\Delta\mu$. If this value was not available, the first photoelectron peak position was estimated directly from the LED-on charge spectrum after the pedestal region. The fit was performed using `scipy.optimize.curve_fit` with parameter bounds to keep the pedestal position, pedestal width, SPE peak position, SPE width, tail fraction, and fitted occupancy within physically meaningful ranges. The model-dependent gain was obtained from the fitted separation between the pedestal and the first photoelectron peak,

$$\Delta\mu = \mu_1 - \mu_0. \quad (22)$$

After conversion from ADC area units to electrons, the gain becomes

$$G_{\text{MD}} = \Delta\mu \, c_{\text{ADC} \rightarrow e}. \quad (23)$$

The uncertainty of the model-dependent gain was determined from the covariance matrix of the fit. Since the gain depends on the difference between μ_1 and μ_0 , the uncertainty of $\Delta\mu$ was calculated as

$$\sigma_{\Delta\mu} = \sqrt{\sigma_{\mu_1}^2 + \sigma_{\mu_0}^2 - 2 \text{Cov}(\mu_1, \mu_0)}. \quad (24)$$

The corresponding gain uncertainty is then

$$\sigma_{G_{\text{MD}}} = \sigma_{\Delta\mu} \, c_{\text{ADC} \rightarrow e}. \quad (25)$$

In addition to the gain, the relative SPE width

$$\frac{\sigma_1}{\Delta\mu}, \quad (26)$$

was extracted as a measure of the single-photoelectron resolution.

4.2.4 Goodness of Fit

The quality of the model-dependent fit was evaluated using residual plots together with a Pearson chi-square test. For each histogram bin, the fitted model prediction was compared to the measured number of entries. The chi-square value was calculated as

$$\chi^2 = \sum_i \frac{(N_i^{\text{obs}} - N_i^{\text{fit}})^2}{N_i^{\text{fit}}}. \quad (27)$$

Only bins with at least five expected entries were included in the calculation. This avoids large statistical fluctuations in sparsely populated regions of the spectrum, where the Gaussian approximation of the counting uncertainty is no longer well justified.

The number of degrees of freedom ν was determined from the number of fitted histogram bins minus the number of free fit parameters. Using this value, the reduced chi-square

$$\chi_\nu^2 = \frac{\chi^2}{\nu}, \quad (28)$$

and the corresponding p -value were calculated. These quantities were used as indicators of the overall fit quality. In addition to the chi-square test, pull residuals were calculated for the residual plots

$$r_i = \frac{N_i^{\text{obs}} - N_i^{\text{fit}}}{\sqrt{N_i^{\text{fit}}}}. \quad (29)$$

The pull residuals show the deviation between the measured spectrum and the fitted model in units of the expected statistical uncertainty. A good fit is expected to produce residuals fluctuating randomly around zero without visible systematic structures. The residual plots were therefore mainly used to identify possible systematic deviations of the fit model.

For each measurement, the analysis script automatically generated a combined figure containing the LED-off and LED-on charge spectra, the fitted pedestal contribution, the individual photoelectron peaks, the total fit model, and the pull residuals. The figures also include the fitted gain values, fit parameters, and goodness-of-fit quantities such as the reduced chi-square and the p -value.

For visualization purposes, the x-axis of the spectra was converted from ADC area units into signal electrons using

$$N_e = \frac{(A - \mu_0)c_{\text{ADC} \rightarrow e}}{10^6}. \quad (30)$$

The numerical results of the model-independent and model-dependent analyses were stored automatically in JSON files. These files contain the gain values, uncertainties, fitted model parameters, covariance information, chi-square results, and histogram data. The saved output was later used for the comparison of different PMTs and different high-voltage settings.

4.3 Afterpulse Analysis

The afterpulse analysis used in this work was also based on the existing `pmt.analysis` package [20]. During this thesis, the code was modified and extended to improve the analysis of the recorded PMT data and to simplify the processing of larger data sets. In addition, the afterpulse analysis was connected directly to the gain analysis, such that the gain values determined from the gain measurements could automatically be used to convert integrated pulse areas from ADC

units into photoelectrons. The extended afterpulse analysis is available in the same GitHub repository as the gain analysis [21].

The pulse search was performed using the `scipy.signal.find_peaks` function. Before the peak search, the waveforms were baseline-subtracted and sign-inverted as described in the gain analysis. The negative PMT pulses therefore appear as positive peaks in the processed waveforms. The peak positions returned by the peak search correspond to the sample indices of the local maxima. The first identified peak in each waveform was treated as the main PMT pulse, while all following peaks were considered afterpulse candidates. For each candidate, the delay relative to the main pulse, the pulse height, and the integrated pulse area were determined.

The separation between the main pulse and an afterpulse candidate was calculated from the difference between their peak positions

$$\Delta n = n_{P_1} - n_{P_0}, \quad (31)$$

where n_{P_0} and n_{P_1} are the sample positions of the local maxima of the main pulse and the afterpulse candidate, respectively. The corresponding delay time was calculated as

$$\Delta t = \frac{\Delta n}{f_{\text{ADC}}}, \quad (32)$$

where $f_{\text{ADC}} = 500 \text{ MHz}$ is the sampling frequency of the digitizer. One sample therefore corresponds to 2 ns .

The integration regions were determined by searching on both sides of each identified peak for points where the waveform returned close to the baseline. Before an afterpulse candidate was accepted, the separation from the main pulse was checked using the minimum waveform amplitude between the two peak positions. The candidate was only considered separated from the main pulse if

$$a_{\text{valley}} \leq 0.05 \cdot \max(a_{P_0}, a_{P_1}), \quad (33)$$

where a_{valley} is the minimum amplitude between the main pulse and the afterpulse candidate, and a_{P_0} and a_{P_1} are their peak amplitudes. This requirement ensures that the waveform has returned close to the baseline before the afterpulse is integrated. The pulse areas were then converted into photoelectrons using the gain calibration

$$A_{\text{PE}} = A_{\text{ADC}} \frac{c_{\text{ADC} \rightarrow e}}{G}, \quad (34)$$

where A_{ADC} is the integrated pulse area in ADC units, $c_{\text{ADC} \rightarrow e}$ is the ADC-area-to-charge conversion factor defined in Eq. (7), and G is the PMT gain.

More than one afterpulse can occur in the same waveform. If the individual pulses were sufficiently separated, they were treated as separate afterpulses. For afterpulse candidates that were close together, however, the determined integration windows could strongly overlap. In some cases, the integration boundaries of two neighbouring candidates differed by no more than five samples, which could lead to the same physical pulse being counted twice.

For these cases, the minimum amplitude between the two afterpulse peaks was determined. The two candidates were treated as separate afterpulses if the minimum fulfilled

$$a_{\text{valley}} \leq 0.3 a_{P_{1,i}} \quad \text{and} \quad a_{\text{valley}} \leq 0.3 a_{P_{1,i+1}}, \quad (35)$$

where $a_{P_{1,i}}$ and $a_{P_{1,i+1}}$ are the amplitudes of the two neighbouring afterpulse peaks. In this case, the integration boundary was placed at the minimum between the two peaks. If this condition was not fulfilled, the candidates were treated as one merged afterpulse and the duplicate entry was removed.

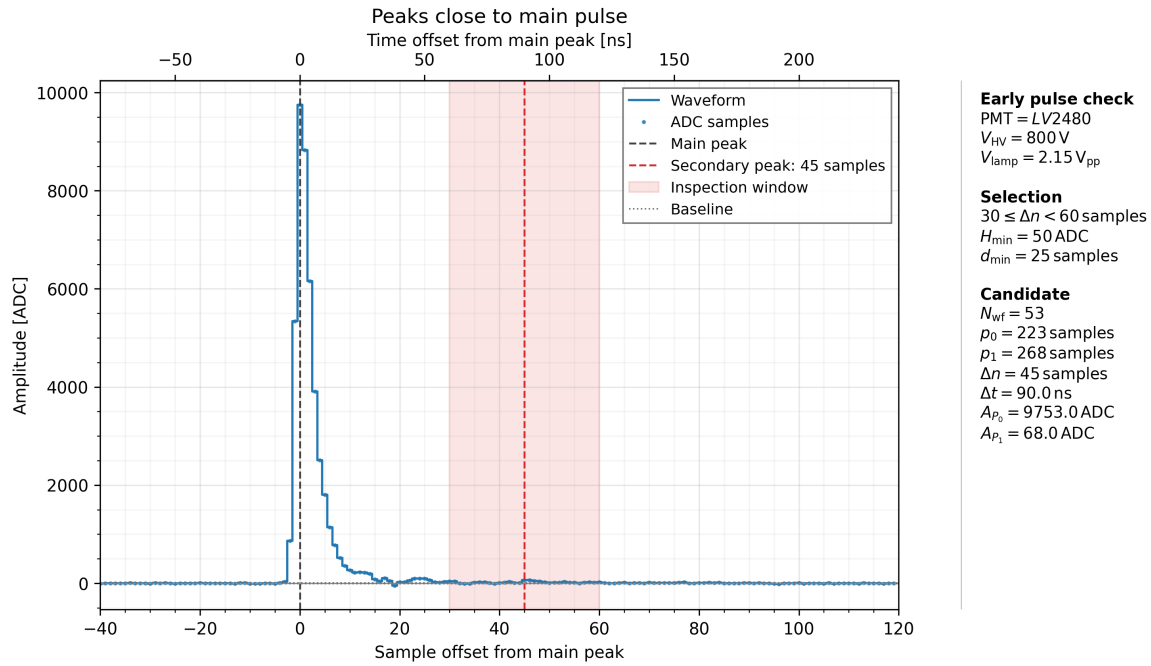


Figure 15: Example waveform showing a small structure shortly after the main PMT pulse that is consistent with ringing rather than an afterpulse. A secondary peak is identified by the peak search, but its amplitude remains below the applied threshold in the close-time selection region and is therefore rejected by the analysis.

Small peaks were also observed shortly after the main PMT pulse. Some of these structures originate from ringing of the main pulse and can therefore be falsely identified as afterpulses. Figure 15 shows an example of such a waveform. A secondary peak is identified shortly after the main pulse, but its small amplitude is consistent with ringing of the main signal. In contrast, Figure 16 shows a larger secondary pulse close to the main PMT signal. The pulse is clearly visible above the small structures following the main signal and is treated as an afterpulse candidate.

The small structures following the main pulse are likely caused by ringing in the readout chain. This can result from signal reflections due to impedance mismatches in the cables and connectors or from the response of the PMT base and the readout electronics to the fast PMT pulse.

To reduce the number of ringing signals identified as afterpulses, an additional selection criterion was applied shortly after the main pulse. Candidates with a separation of less than 10 samples from the main pulse were rejected. For separations between 10 and 60 samples, corresponding to approximately 20 ns to 120 ns, a candidate was only accepted if its peak amplitude was at least 100 ADC. Afterpulse candidates with larger delays were treated without this additional amplitude requirement. This selection suppresses small ringing structures close to the main pulse while retaining larger afterpulse signals in the same time region.

The final afterpulse rate was determined from the number of identified afterpulses normalized to the total main-pulse charge in photoelectrons

$$\frac{R_{AP}}{PE} = \frac{N_{AP}}{\sum_k A_{P_0,k}^{PE}}, \quad (36)$$

where N_{AP} is the total number of identified afterpulses and $A_{P_0,k}^{PE}$ is the integrated main-pulse area of waveform k expressed in photoelectrons.

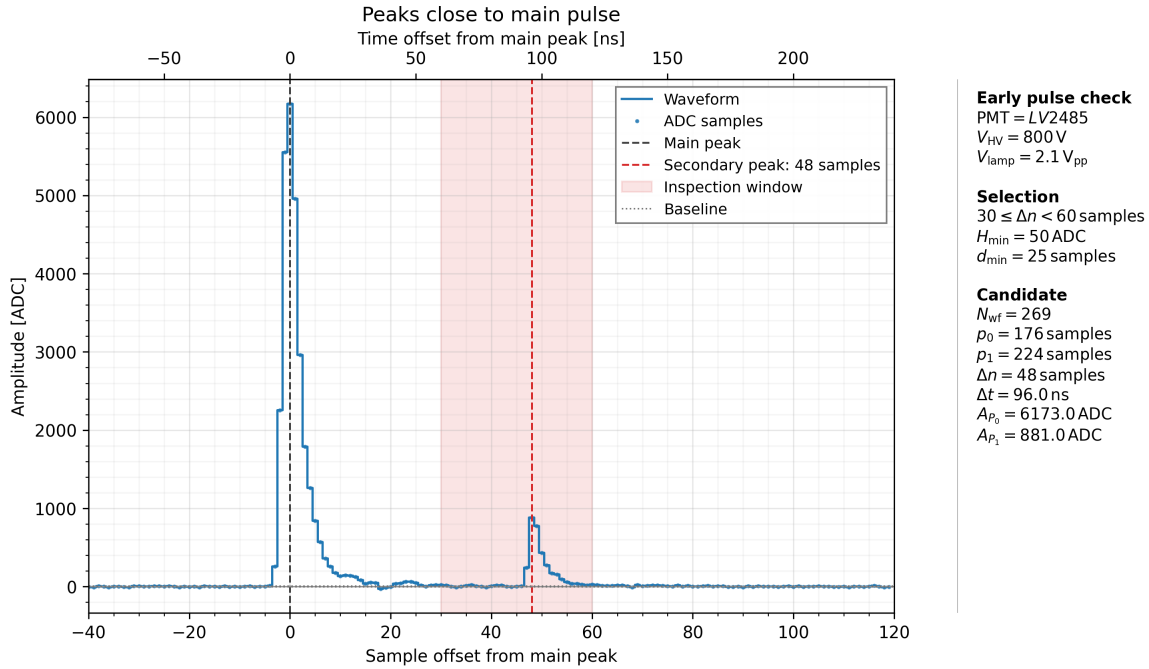


Figure 16: Example waveform containing a secondary pulse shortly after the main PMT signal. The secondary peak satisfies the afterpulse selection criteria and is treated as an afterpulse candidate.

The statistical uncertainty of the afterpulse rate was estimated assuming Poisson fluctuations of the number of identified afterpulses,

$$\sigma\left(\frac{R_{AP}}{PE}\right) = \frac{\sqrt{N_{AP}}}{\sum_k A_{P_0,k}^{PE}}. \quad (37)$$

To reduce the computational load, the full data set was processed in smaller chunks. Diagnostic plots were produced using smaller waveform samples, while the final numerical results were calculated from the complete data set. Summary plots were also produced to compare the afterpulse behaviour of the four investigated PMTs. In addition to the total afterpulse distributions, afterpulses with integrated areas below and above 2 PE were studied separately.

5 Results

This section presents the results of the PMT characterization measurements. At the beginning of this study, ten Hamamatsu R8520 PMTs were available, as listed in Table 1. From these, four PMTs were selected for detailed characterization. They are referred to by their serial numbers LV2480, LV2481, LV2483, and LV2485 throughout this thesis. The serial numbers are used to distinguish the individual PMTs in the following figures and tables.

The four PMTs were characterized using gain and afterpulse measurements in order to compare their performance and suitability for use in the detector.

5.1 Gain

The gain analysis was performed for all four investigated PMTs at several high-voltage settings between 700 V and 900 V. For each measurement, the integrated charge spectrum was fitted

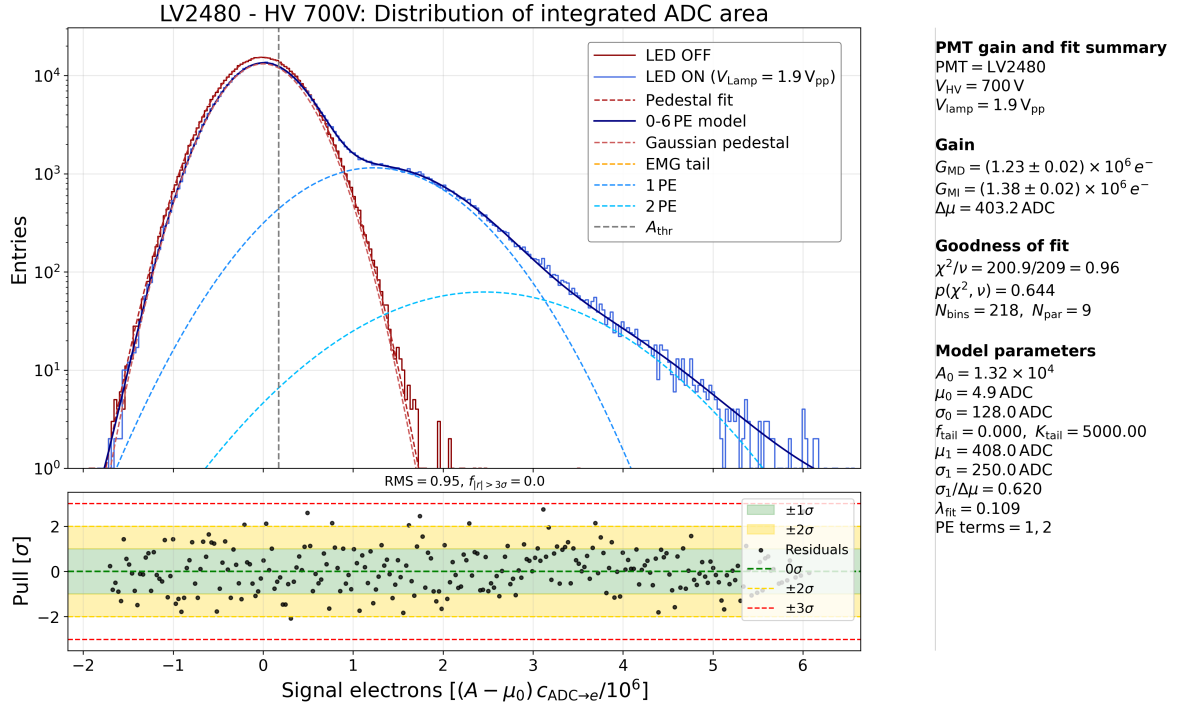


Figure 17: Integrated charge spectrum of PMT LV2480 measured at 700 V. At this voltage, the single-photoelectron signal is only partially separated from the pedestal. The fitted model components and the pull residuals are shown.

using the model described in Section 4.2. Example fit results for PMT LV2480 are shown in Figures 17, 18 and 19 for different voltages. The remaining fit plots are provided in Appendix A.

The fitted charge spectra show a clear separation between the pedestal and the single-photoelectron signal. As the applied high voltage increases, the distance between the photoelectron peaks becomes larger, reflecting the increase in PMT gain. At the same time, the relative width of the single-photoelectron peak becomes smaller, indicating an improvement in the charge resolution at higher voltages.

Figure 20 shows the model-dependent gain as a function of the applied high voltage for all investigated PMTs. The gain increases strongly with increasing high voltage for all four PMTs. The voltage dependence was fitted with a power-law function

$$G(V) = AV^k, \quad (38)$$

where A is a normalization parameter and k describes the voltage dependence of the gain. The fitted values of k are similar for all four PMTs and range from 8.15 ± 0.24 for PMT LV2480 to 8.53 ± 0.14 for PMT LV2483. This shows that the gain follows a similar voltage dependence for the investigated PMTs, although differences in the absolute gain values can be observed between the individual tubes.

At 800 V, the measured gains range from approximately 3.53×10^6 for PMT LV2481 to about 4.94×10^6 for PMT LV2485. PMTs LV2480 and LV2483 show intermediate values of approximately 4.24×10^6 and 4.06×10^6 , respectively.

The numerical gain values obtained from the model-dependent fits are summarized in Table 3.

Table 4 compares the measured gains at 800 V with the gain values reported directly by Hamamatsu seen in Table 1. The relative difference was calculated as

$$\Delta G = \frac{G_{\text{measured}} - G_{\text{Hamamatsu}}}{G_{\text{Hamamatsu}}} \times 100\%. \quad (39)$$

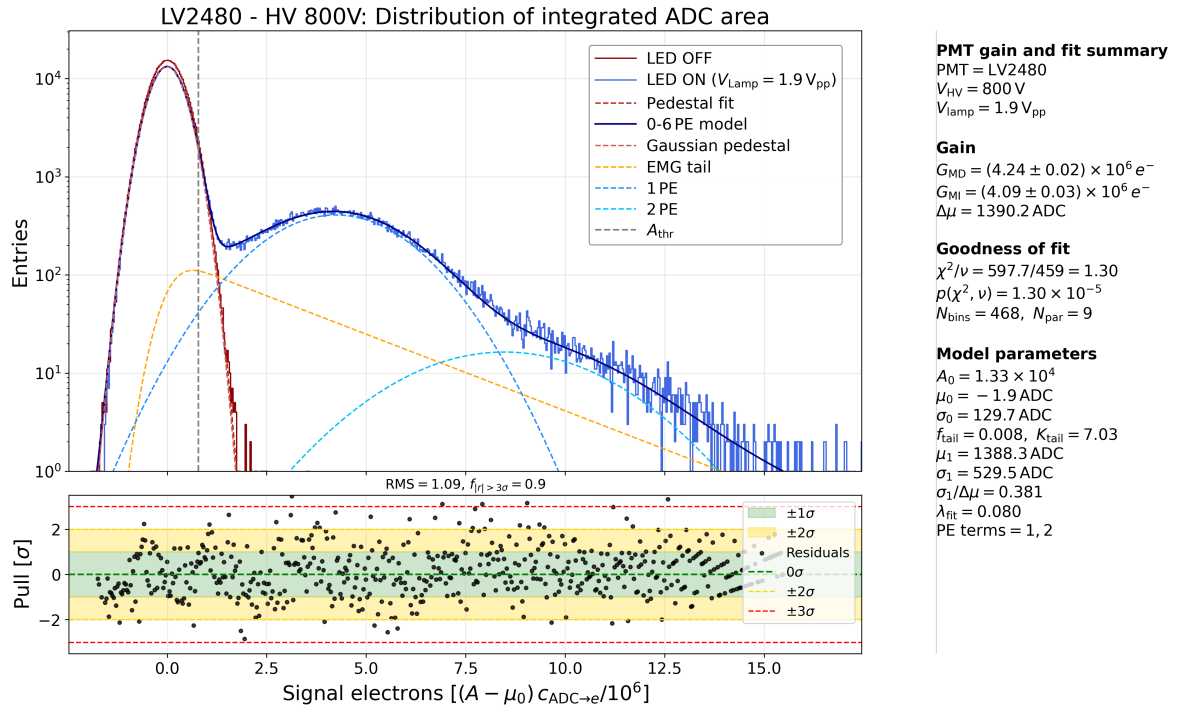


Figure 18: Integrated charge spectrum of PMT LV2480 measured at 800 V. The increased gain leads to a clearer separation between the pedestal and the single-photoelectron signal. The fitted model components and the pull residuals are shown.

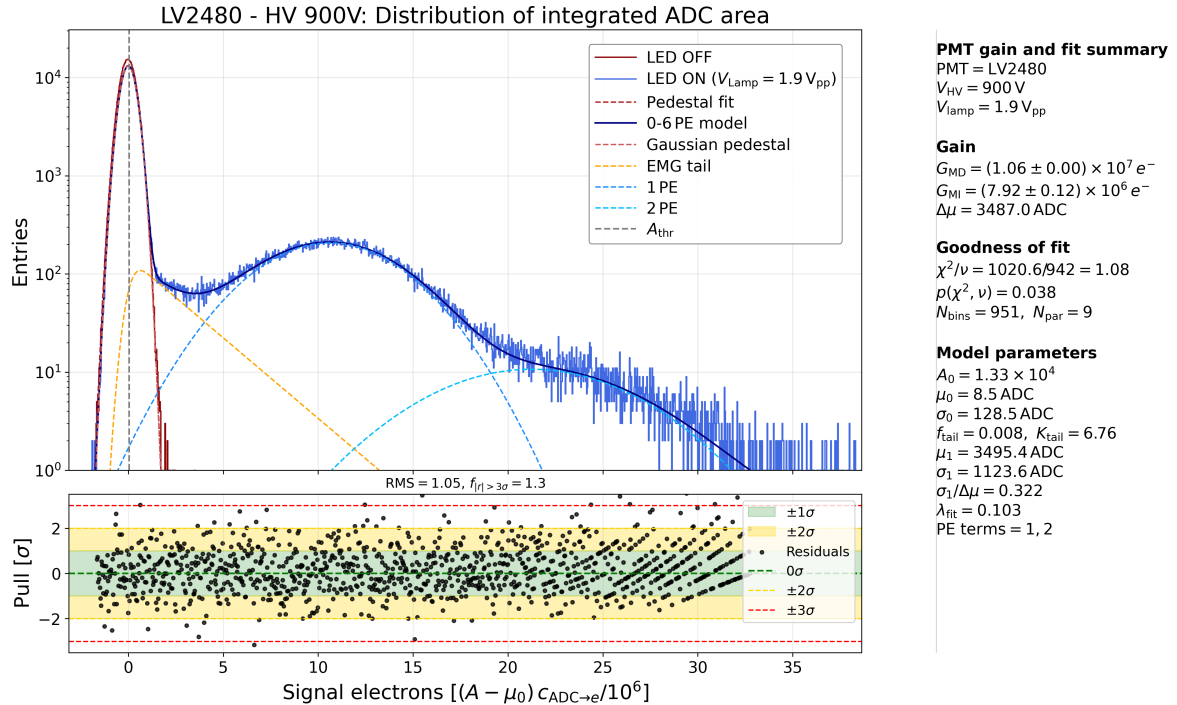


Figure 19: Integrated charge spectrum of PMT LV2480 measured at 900 V. Compared to lower voltages, the larger gain leads to a clearer separation between the pedestal and the single-photoelectron signal. The fitted model components together with the pull residuals are shown.

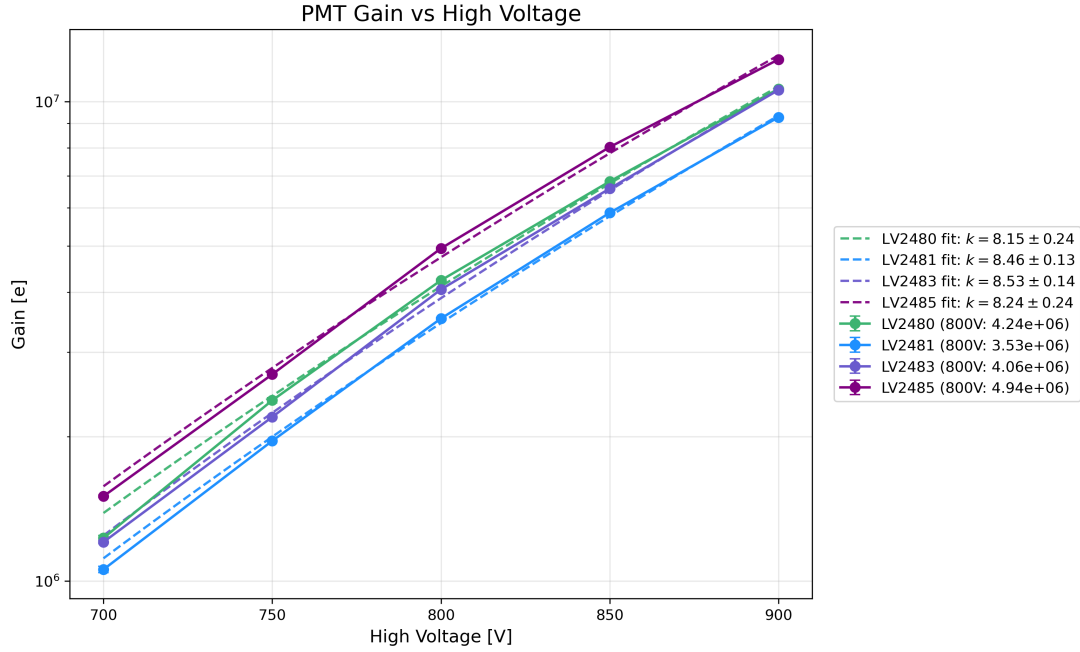


Figure 20: Measured model-dependent PMT gain as a function of the applied high voltage for the four investigated R8520 PMTs. The markers show the measured gain values, and the solid lines connect the data points. The dashed lines show power-law fits of the form $G(V) = AV^k$. The statistical uncertainties are shown as error bars but are smaller than the markers.

HV [V]	LV2480	LV2481	LV2483	LV2485
700	$(1.23 \pm 0.02) \times 10^6$	$(1.05 \pm 0.02) \times 10^6$	$(1.20 \pm 0.01) \times 10^6$	$(1.48 \pm 0.01) \times 10^6$
750	$(2.34 \pm 0.03) \times 10^6$	$(1.96 \pm 0.01) \times 10^6$	$(2.18 \pm 0.01) \times 10^6$	$(2.73 \pm 0.01) \times 10^6$
800	$(4.24 \pm 0.02) \times 10^6$	$(3.53 \pm 0.01) \times 10^6$	$(4.06 \pm 0.01) \times 10^6$	$(4.94 \pm 0.01) \times 10^6$
850	$(6.81 \pm 0.03) \times 10^6$	$(5.87 \pm 0.01) \times 10^6$	$(6.73 \pm 0.02) \times 10^6$	$(8.02 \pm 0.01) \times 10^6$
900	$(1.06 \pm 0.003) \times 10^7$	$(9.24 \pm 0.02) \times 10^6$	$(1.05 \pm 0.001) \times 10^7$	$(1.23 \pm 0.002) \times 10^7$

Table 3: Measured model-dependent gain values for the four investigated R8520 PMTs at different applied high voltages. The quoted uncertainties are statistical uncertainties obtained from the covariance matrix of the charge-spectrum fit and propagated to the gain.

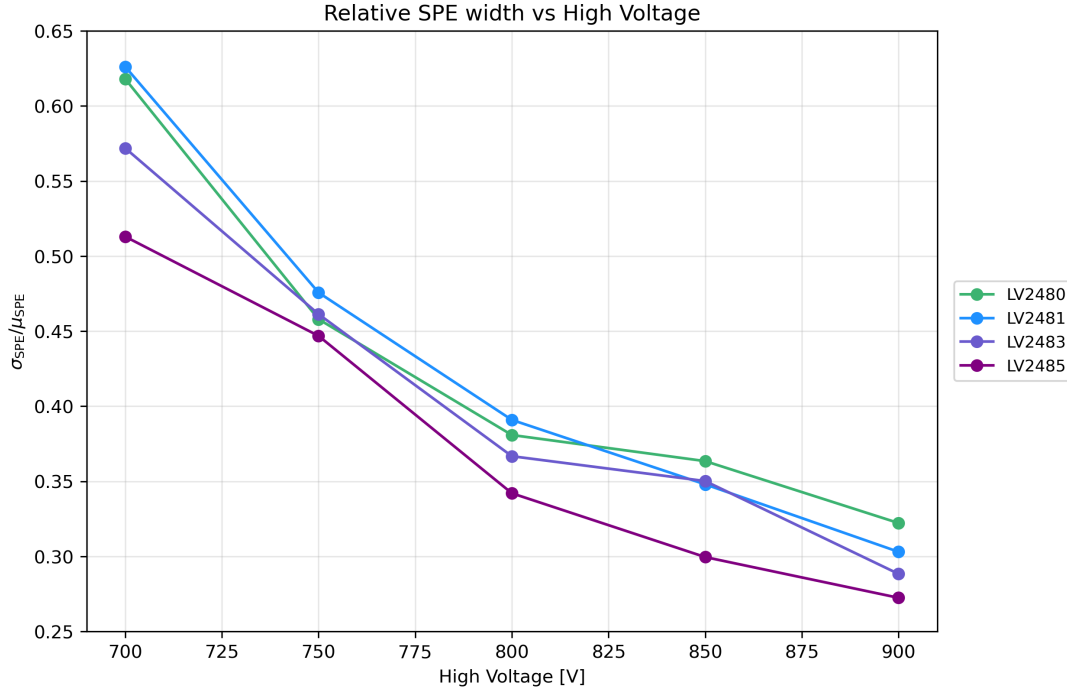


Figure 21: Relative single-photoelectron width $\sigma_{\text{SPE}}/\mu_{\text{SPE}}$ as a function of the applied high voltage for the four investigated PMTs. The markers show the measured values, while the solid lines connect the data points. The relative SPE width decreases with increasing high voltage, indicating an improvement in the SPE charge resolution.

PMT	G_{measured}	$G_{\text{Hamamatsu}}$	Difference
LV2480	4.24×10^6	4.1×10^6	+3.4 %
LV2481	3.53×10^6	3.3×10^6	+7.0 %
LV2483	4.06×10^6	3.7×10^6	+9.7 %
LV2485	4.94×10^6	3.8×10^6	+30.0 %

Table 4: Comparison of the measured gains at 800 V with the gain values reported directly by Hamamatsu. The difference is expressed relative to the Hamamatsu value.

The measured gains of PMTs LV2480, LV2481, and LV2483 agree with the values reported by Hamamatsu within approximately 10 %. PMT LV2485 shows a larger deviation of approximately 30 %, although its gain follows the same voltage-dependent behaviour as the other investigated PMTs.

Figure 21 shows the relative single-photoelectron width, $\sigma_{\text{SPE}}/\mu_{\text{SPE}}$, as a function of the applied high voltage. For all investigated PMTs, the relative SPE width decreases with increasing voltage. This indicates that the charge resolution improves at higher gain values. The largest improvement is observed between 700 V and 800 V, while the decrease becomes smaller at higher voltages.

As described in Section 4.2.4, the quality of the fits was evaluated using residual distributions and Pearson chi-square tests. In most cases, the fitted model describes the measured spectra well over the full charge range. The residual distributions are approximately centred on zero without strong systematic structures, indicating that the model reproduces the main features of the measured spectra reasonably well. In the high-charge tail, the pull values show a banded structure because only a small number of entries is present in each histogram bin. The measured bin contents therefore take discrete integer values, while the fitted model varies continuously.

This causes bins with the same number of entries to form visible bands. Since this region contains fewer entries, statistical fluctuations are also larger and small differences between the data and the fit become more visible. However, the gain determination depends mainly on the fitted separation between the pedestal and the first photoelectron peak and is therefore only weakly affected by these deviations.

Overall, all investigated PMTs show the expected increase in gain with increasing high voltage and stable single-photoelectron spectra over the investigated operating voltage range.

5.2 Afterpulses

The afterpulse analysis was performed for all four investigated PMTs using the analysis procedure described in Section 4.3. All afterpulse measurements were carried out at an applied high voltage of 800 V. The recorded waveforms contained 2500 samples, corresponding to a total waveform length of $5\,\mu\text{s}$ at the sampling frequency of 500 MHz. For each PMT, several diagnostic plots were produced in order to study the afterpulse properties in more detail.

Example plots for PMT LV2480 are shown in Figures 22–27. Similar plots were generated for all investigated PMTs. Since the overall behaviour was very similar for all measurements, only representative examples are shown in the main text, while the remaining plots are included in Appendix B.

Figure 22 shows the distribution of the measured afterpulse areas in units of photoelectrons. Most identified afterpulse candidates are located at relatively small pulse areas below 2 PE. The number of events decreases continuously towards larger pulse areas, although individual afterpulses with amplitudes above 10 PE are still visible. The comparison between all identified afterpulse candidates and the subset of separable afterpulses shows only small differences. This indicates that only a limited number of overlapping or merged pulses were present and that the analysis script was able to separate most merged afterpulse signals successfully.

The relation between afterpulse area and delay time relative to the main pulse is shown in Figure 23. Most afterpulses occur within the first microsecond after the main PMT signal. A higher concentration of events can be observed between approximately $0.2\,\mu\text{s}$ and $0.8\,\mu\text{s}$. In this region, most afterpulses have relatively small amplitudes below about 2 PE. Larger afterpulse signals appear less frequently and are distributed over a wider time range.

Several example waveforms identified by the analysis are shown in Figure 24. In these waveforms, the main PMT pulse is followed by one or more secondary pulses occurring several hundred nanoseconds later. The highlighted regions show the integration windows of the main pulse and one selected afterpulse candidate. Other secondary pulses visible in the waveforms were also identified as afterpulses, but only one afterpulse is highlighted in each panel for clarity.

Figure 25 shows the time-difference distribution for PMT LV2480. The largest number of afterpulse candidates is observed shortly after the main pulse, followed by a gradual decrease towards larger delay times. Even though the number of events decreases at larger delay times, afterpulse candidates are still visible above $2\,\mu\text{s}$. The waveform length of $5\,\mu\text{s}$ limits the time range covered by the measurement and therefore defines the maximum delay time accessible in the afterpulse analysis.

The main results of the afterpulse measurements are summarized in Figure 26, where the relative afterpulse rates are compared for all four investigated PMTs. The relative afterpulse rate is defined as the number of identified afterpulses normalized to the total main-pulse charge in photoelectrons. In addition to the total relative afterpulse rate, the contributions from afterpulses above and below an area threshold of 2 PE are shown separately. The corresponding numerical values are listed in Table 5.

The comparison shows clear differences between the investigated PMTs. PMT LV2485

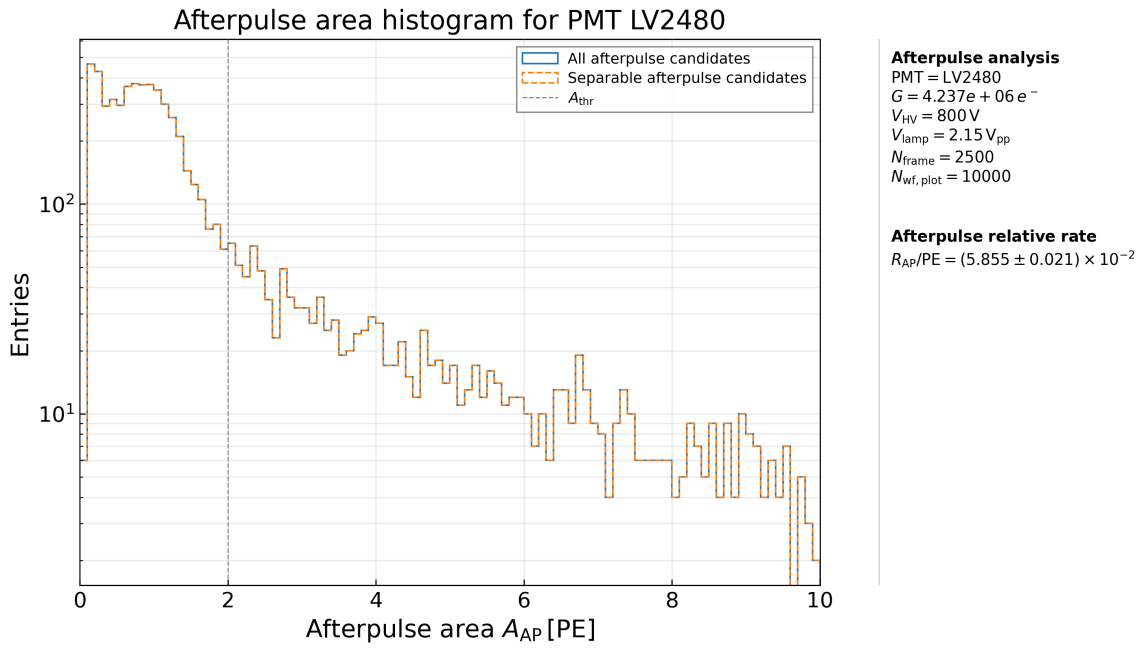


Figure 22: Distribution of the measured afterpulse areas for PMT LV2480 at an applied high voltage of 800 V. Most identified afterpulse candidates are concentrated at small pulse areas below approximately 2 PE, while larger afterpulse signals occur less frequently. The dashed vertical line indicates the applied threshold of $A_{thr} = 2$ PE used to separate small and large afterpulses.

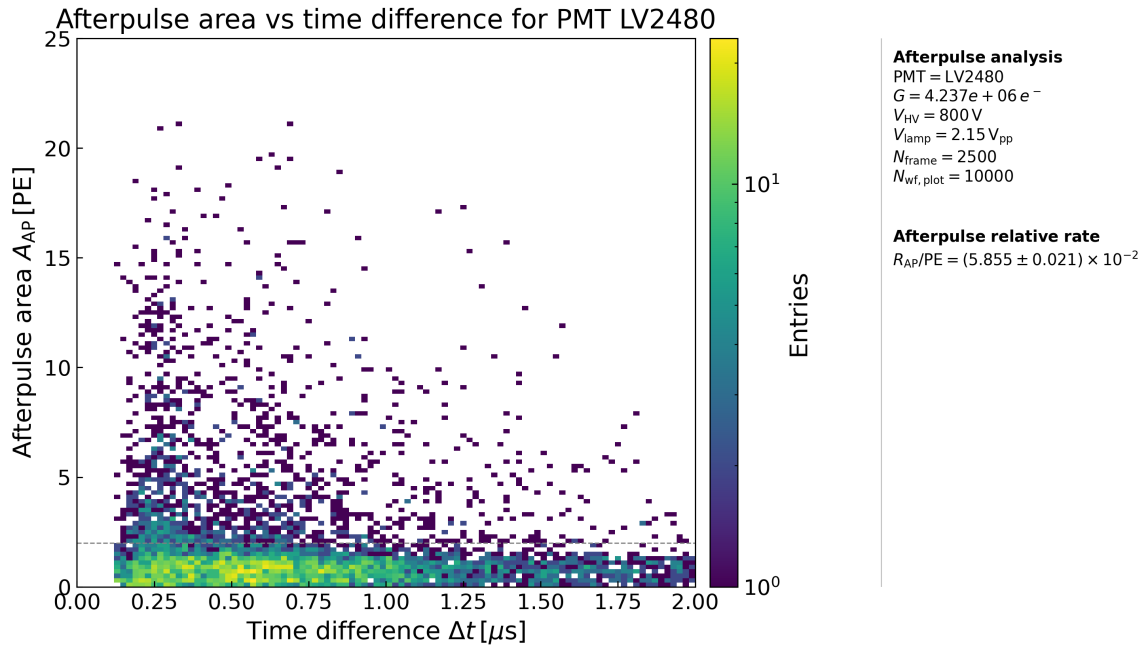


Figure 23: Correlation between afterpulse area and delay time for PMT LV2480 measured at an applied high voltage of 800 V. Most afterpulse candidates occur within the first microsecond after the main PMT pulse and are concentrated at relatively small pulse areas below approximately 2 PE. Larger afterpulse signals occur less frequently and are distributed over a wider range of delay times.

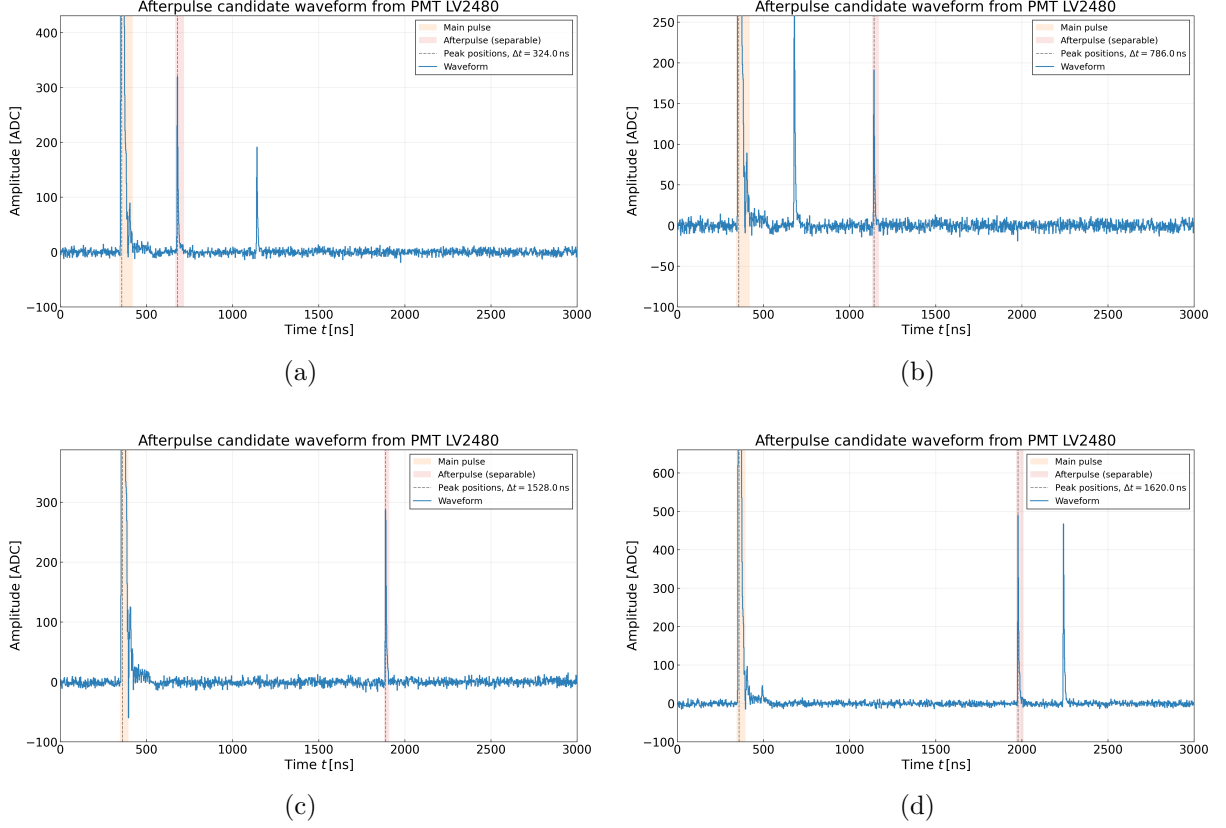


Figure 24: Example afterpulse candidate waveforms measured for PMT LV2480 at an applied high voltage of 800 V. The highlighted regions indicate the integration windows of the main PMT pulse and one selected afterpulse candidate. In some panels, additional afterpulses are visible. These were also identified and treated separately by the analysis, but only one afterpulse candidate is highlighted in each panel for clarity.

PMT	Total R_{AP}/PE	$A_{AP} \geq 2 PE$	$A_{AP} < 2 PE$
LV2480	$(5.855 \pm 0.021) \times 10^{-2}$	$(1.355 \pm 0.010) \times 10^{-2}$	$(4.500 \pm 0.018) \times 10^{-2}$
LV2481	$(6.537 \pm 0.012) \times 10^{-2}$	$(1.671 \pm 0.006) \times 10^{-2}$	$(4.866 \pm 0.010) \times 10^{-2}$
LV2483	$(3.542 \pm 0.006) \times 10^{-2}$	$(0.816 \pm 0.003) \times 10^{-2}$	$(2.726 \pm 0.005) \times 10^{-2}$
LV2485	$(1.495 \pm 0.002) \times 10^{-1}$	$(3.073 \pm 0.009) \times 10^{-2}$	$(1.188 \pm 0.002) \times 10^{-1}$

Table 5: Measured relative afterpulse rates for the four investigated PMTs at an applied high voltage of 800 V. The relative afterpulse rate is defined as the number of identified afterpulses normalized to the total main-pulse charge in photoelectrons. The total relative rate is separated into contributions from afterpulses above and below an area threshold of 2 PE. The quoted uncertainties are statistical uncertainties.

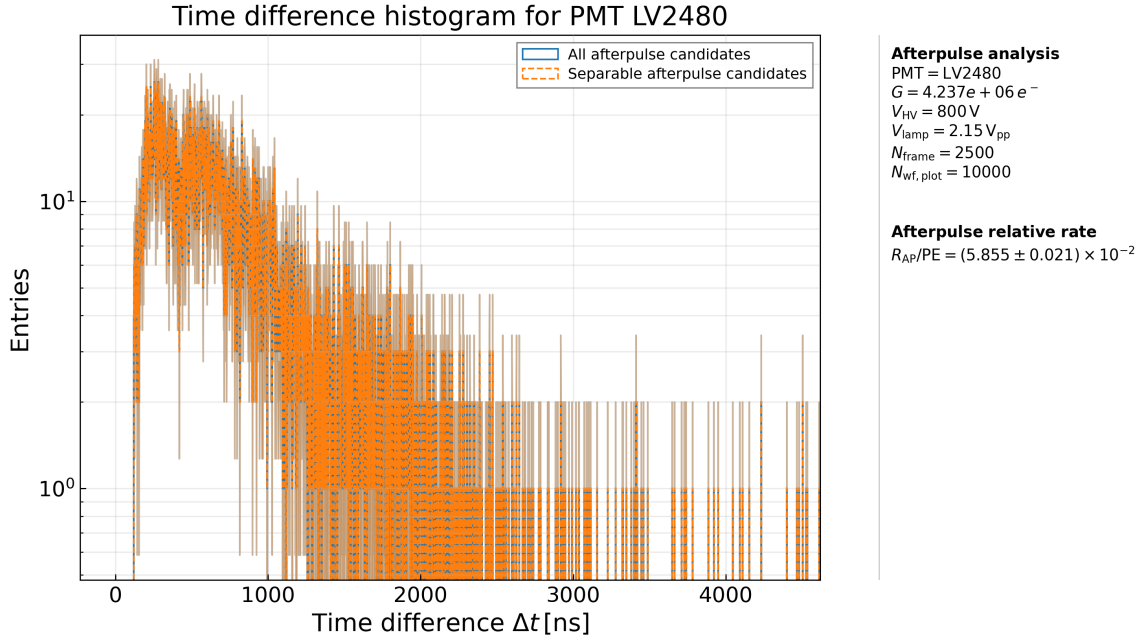


Figure 25: Distribution of the delay times between the main PMT pulse and the identified afterpulse candidates for PMT LV2480 at an applied high voltage of 800 V. The largest number of afterpulse candidates is observed shortly after the main pulse, followed by a gradual decrease towards larger delay times. Afterpulse candidates are still visible at delay times above $2 \mu s$. The accessible delay-time range is limited by the $5 \mu s$ waveform length.

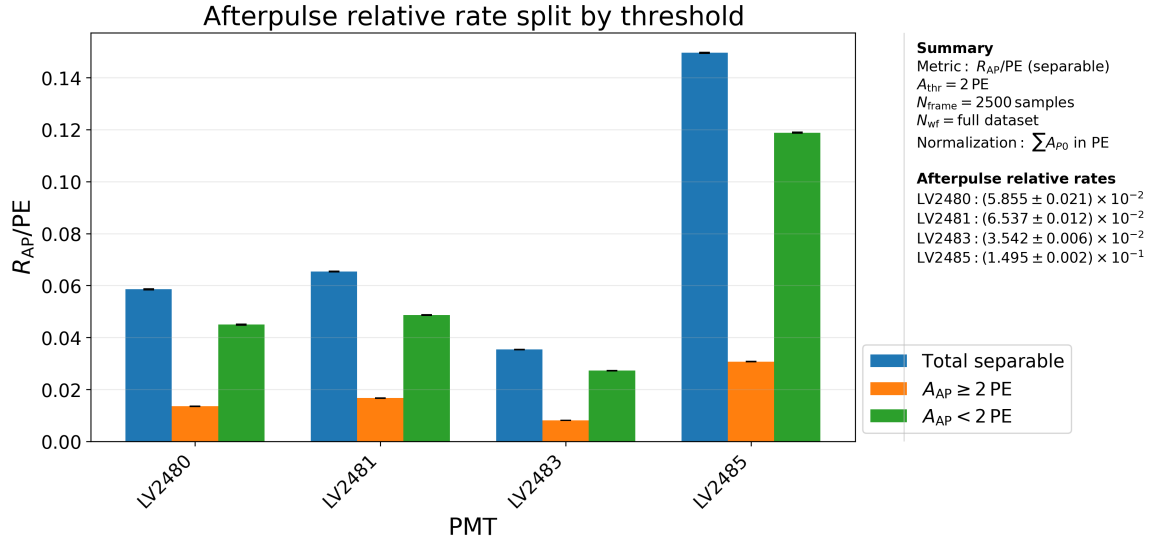


Figure 26: Comparison of the relative afterpulse rates for the four investigated PMTs measured at an applied high voltage of 800 V. In addition to the total relative afterpulse rate, the contributions from afterpulses above and below an area threshold of 2 PE are shown separately. For all PMTs, the dominant contribution originates from afterpulses with areas below 2 PE. PMT LV2485 shows the highest relative afterpulse rate, while LV2483 shows the lowest rate.

exhibits the highest relative afterpulse rate, with a value of approximately 0.150, which is significantly larger than the values measured for the other PMTs. In contrast, LV2483 shows the lowest relative afterpulse rate, with a value of approximately 0.035. PMTs LV2480 and LV2481 lie between these two values and show comparable afterpulse behaviour.

For all investigated PMTs, most afterpulse signals have areas below 2 PE. Larger afterpulses above this threshold contribute only a relatively small part of the total relative afterpulse rate.

Figure 27 shows the fraction of afterpulses with amplitudes above 2 PE relative to the total afterpulse rate for the investigated PMTs.

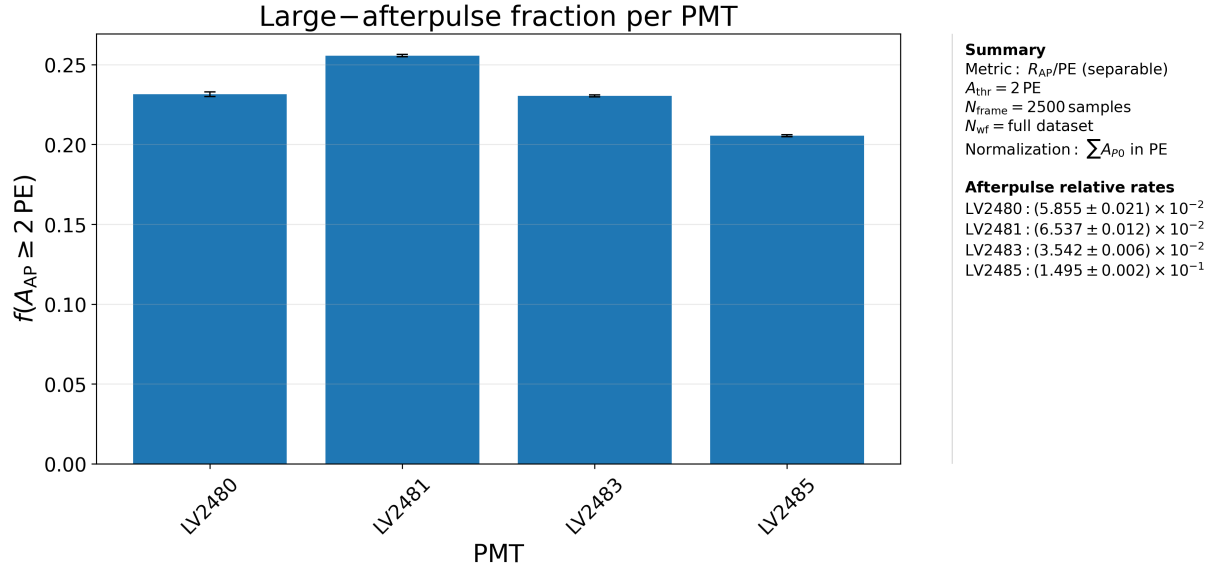


Figure 27: Fraction of afterpulses with pulse areas above 2 PE relative to the total afterpulse rate for the four investigated PMTs measured at an applied high voltage of 800 V. All PMTs show comparable fractions of large afterpulses, indicating that the observed differences in the total afterpulse rates are mainly caused by variations in the number of small afterpulse signals.

Overall, the investigated R8520 PMTs show similar afterpulse distributions, with most afterpulse signals appearing at short delay times and with relatively small areas. However, clear differences are observed in the relative afterpulse rates of the individual PMTs, with LV2483 showing the lowest rate and LV2485 the highest.

6 PMT Selection and Conclusions

In this part of the thesis, the gain and afterpulse behaviour of four Hamamatsu R8520 PMTs was investigated at different operating voltages. The existing analysis framework was extended and adapted to the recorded PMT data to allow for the gain and afterpulse measurements to be processed in a consistent way.

The gain measurements showed the expected increase in gain with increasing high-voltage for all four PMTs. At higher voltages, the single-photoelectron peaks were more clearly separated from the pedestal and the relative SPE width decreased. The gain values obtained from the measurements were also in reasonable agreement with the values calculated from the Hamamatsu test data. Overall, the four PMTs showed a similar gain behaviour, although differences in the absolute gain values were observed.

For a direct comparison of the investigated PMTs, the measured gain at an applied high voltage of 800 V and the total afterpulse rate per photoelectron are summarized in Table 6.

PMT	Gain at 800 V	Total R_{AP}/PE
LV2480	$(4.24 \pm 0.02) \times 10^6$	$(5.855 \pm 0.021) \times 10^{-2}$
LV2481	$(3.53 \pm 0.01) \times 10^6$	$(6.537 \pm 0.012) \times 10^{-2}$
LV2483	$(4.06 \pm 0.01) \times 10^6$	$(3.542 \pm 0.006) \times 10^{-2}$
LV2485	$(4.94 \pm 0.01) \times 10^6$	$(1.495 \pm 0.002) \times 10^{-1}$

Table 6: Summary of the measured gain at an applied high voltage of 800 V and the total afterpulse rate for the investigated PMTs.

The afterpulse measurements showed larger differences between the individual PMTs. Most afterpulses occurred at short delay times and had small pulse areas below 2 PE. As can also be seen from Table 6, LV2480 and LV2483 showed lower total afterpulse rates than LV2481 and LV2485. LV2485, for example, showed the highest gain at 800 V but also a considerably higher afterpulse rate.

For the cross detector, a low afterpulse rate is important because afterpulses produce additional PMT signals after the initial light signal. These delayed signals could be interpreted as additional scintillation light and therefore affect the detector response. For this reason, the PMT selection was not based on the gain alone.

Based on the gain and afterpulse measurements, LV2480 and LV2483 were selected for the cross detector. Both PMTs showed similar and stable gain behaviour and had lower afterpulse rates than the other two investigated PMTs. They therefore provided the best combination of gain and afterpulse behaviour for the detector. LV2480 and LV2483 were subsequently used for the assembly of the cross detector described in the following part of this thesis.

Part III

Cross Detector

In this part, the design and construction of the cross detector used in this thesis are described. The chapter introduces the detector concept, explains the motivation behind the chosen geometry, and presents the assembly and integration of the detector into the xenon gas system.

7 Cross Detector

7.1 Design

The concept for the cross detector was originally developed at the University of Münster for scintillation measurements in gaseous xenon [24]. For this thesis, the design was adapted to the experimental setup at the University of Zurich.

Random dark counts from the PMTs can contribute to the measured background. Since these signals occur independently in each PMT, their contribution can be reduced by using two PMTs and requiring a coincidence between them. A scintillation event should produce light that is detected by both PMTs at approximately the same time, while random dark counts are unlikely to occur simultaneously.

The detector consists of two stainless-steel tubes connected perpendicularly by a CF40 cross piece. Two Hamamatsu R8520 PMTs are mounted opposite each other along one detector axis, while the xenon gas flows through the tube along the other axis. The intersection of the two tubes forms the active scintillation volume. The cables from the PMT bases lead to CF40 flanges at the two ends of the detector. Each flange contains two electrical feedthroughs, one for the PMT signal and one for the high-voltage connection. Figure 29 gives an overview of the main detector components. It shows the positions of the two PMTs, the PTFE reflector, and the direction of the xenon gas flow.

The active volume is surrounded by a PTFE reflector. PTFE has a high reflectivity for xenon scintillation light in the vacuum-ultraviolet wavelength range. Its reflection is mainly diffuse rather than specular. The curved inner surface of the reflector improves the probability that reflected photons reach one of the two photocathodes. A detailed description of the original reflector design can be found in Ref. [24].

Several mechanical changes were made to adapt the original design. A single PTFE holder was used instead of two separate support pieces. Its dimensions were adjusted so that it could be inserted past the welding seams inside the CF40 cross. Openings in the holder allow the enclosed volumes to be pumped efficiently. PEEK nuts were inserted into the metal parts used to secure the holder. This electrically isolates the PMTs from the metal rods and reduces the risk of high-voltage discharges. These changes simplified the assembly while keeping a flush PTFE surface around the PMTs and the active volume.

7.2 Assembly

Before assembly, the detector components were cleaned to remove dust, grease, and residues left from machining. The stainless-steel parts were cleaned in an ultrasonic bath using a (95:5) mixture of deionized water and ELMA 60. After the ultrasonic cleaning, the parts were rinsed with deionized water and dried in a desiccator. The PTFE components were cleaned following the same procedure, using ELMA 65 instead of ELMA 60. The cables and electrical feedthrough flanges were cleaned carefully by hand using ethanol and lint-free wipes.

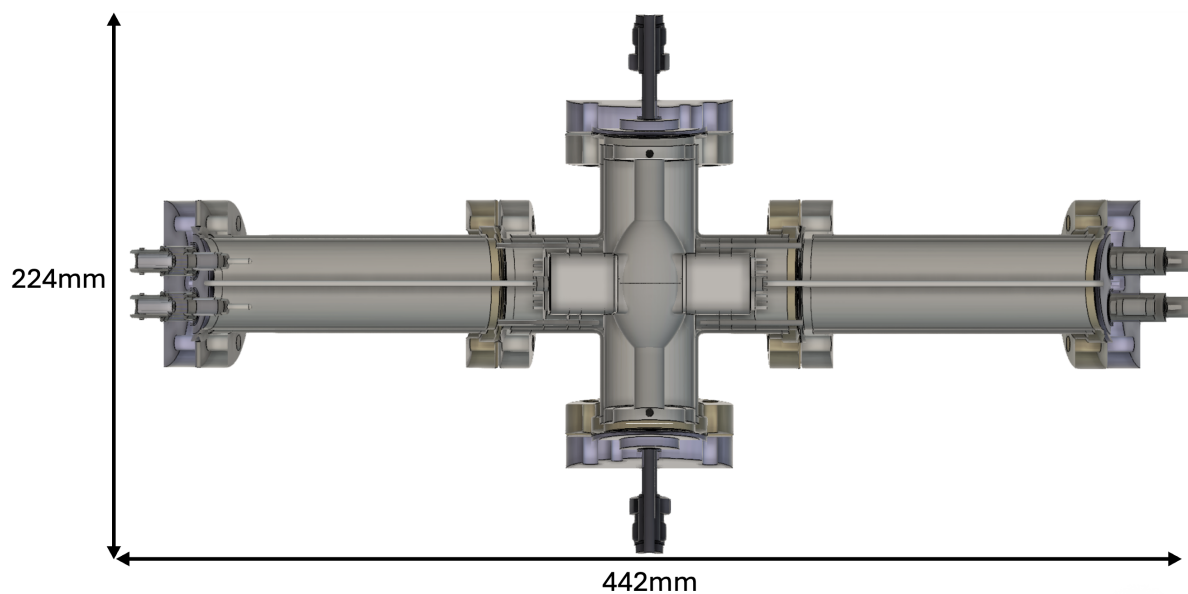


Figure 28: Cross-sectional CAD drawing of the cross detector. The two PMTs are mounted opposite each other and observe the central scintillation volume. The xenon gas flows through the tube along the other detector axis.

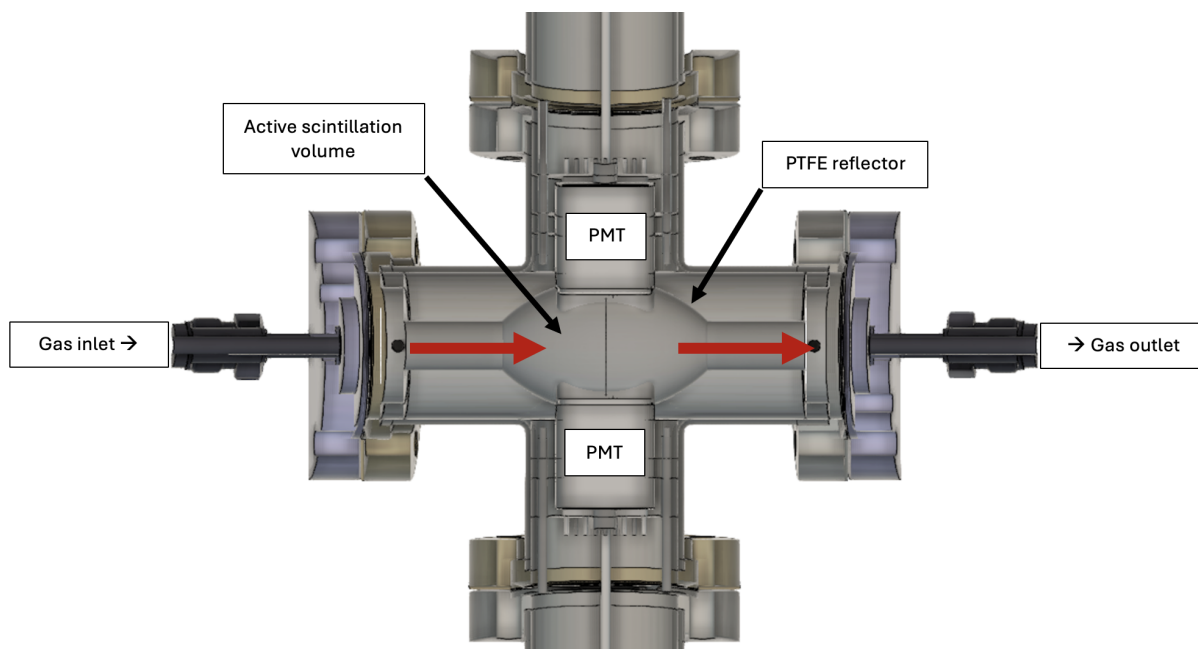


Figure 29: Annotated cross-sectional CAD drawing of the cross detector, showing the two opposing PMTs, the PTFE reflector around the active volume, and the direction of the xenon gas flow.

The stainless-steel detector body was equipped with the gas connections, the PTFE reflector, and the two selected Hamamatsu R8520 PMTs. The PMTs were mounted opposite each other in the PTFE holders. These holders kept the PMTs in the correct position and electrically insulated them from the stainless-steel housing.

The installation of one PMT together with its PTFE holder is shown in Figure 30. The holder positions the PMT window next to the active scintillation volume and provides mechanical support and electrical insulation.



Figure 30: One of the selected R8520 photomultiplier tubes mounted in its PTFE holder during assembly. The holder provides mechanical support and electrical insulation from the surrounding metal components.

Figure 31 shows the view through the gas-flow tube after the PMTs and the PTFE reflector had been installed. The PTFE reflector surrounds the active scintillation volume, and one of the PMTs is visible on the opposite side. Scintillation light produced in the active volume can therefore be detected by both PMTs.

After all components had been installed, the detector was closed and prepared for connection to the gas system. Figure 32 shows the fully assembled detector. The two opposing PMTs are located along one detector axis, while the tube along the other axis forms the gas-flow path through the active scintillation region.

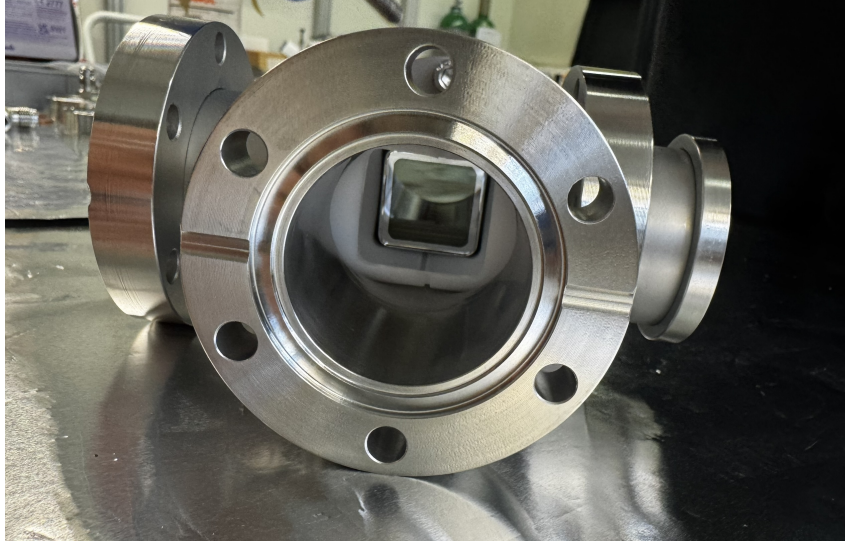


Figure 31: View through the gas-flow tube during assembly. The PTFE reflector surrounds the active scintillation volume, while one of the opposing PMTs is visible on the other side of the detector.



Figure 32: Photograph of the fully assembled cross detector before installation into the experimental setup. The two opposing PMTs are mounted along one detector axis, while the tube along the other axis forms the gas-flow path through the active scintillation region.

8 Gas System

8.1 Experimental Setup

For future measurements with radioactive calibration sources, the cross detector will be operated using the gaseous xenon circulation system at the University of Zurich. A schematic overview of the modified system is shown in Figure 33.

The gas system was previously used as part of MarmotX, a liquid-xenon setup for testing photomultiplier tubes. This included measurements of the 3-inch R11410-21 and 2-inch R12699-406-M4 PMT models [19, 25]. Several changes were made to prepare the system for the cross detector and future measurements with ^{79}Kr .

Compared with the previous MarmotX configuration, two new Omega PX302 pressure transducers were installed. One is located downstream of the circulation pump (KNF N022 ANE), while the other is positioned close to the cross detector. The getter purifier was replaced with a new heated rare-gas getter purifier (Gaspuri RGGP5-L). A bypass equipped with a regulating valve was added around the circulation pump to adjust the gas flow through the main loop. A separate line was installed for the cross detector, including the nearby pressure transducer and a dedicated vacuum-pump port. Finally, a ^{79}Kr source line was added for future calibration measurements.

The xenon is supplied from high-pressure gas bottles and passes through a pressure reducer before entering the circulation loop. The gas is circulated by a membrane pump and passes through the getter purifier, which removes impurities from the xenon and helps to maintain a high optical transparency for vacuum-ultraviolet scintillation photons. The gas flow is measured using a Teledyne Hastings HFM-D-300 flow meter located in the main circulation line downstream of the getter.

During operation, the pressure is monitored using the two Omega PX302 pressure transducers, while the gas flow is measured using the HFM-D-300 flow meter. The pressure and flow values are read manually and are not controlled automatically. The gas flow can be adjusted manually using the regulating valve in the pump-bypass line. Additional manually operated valves allow individual parts of the system to be isolated, evacuated, or bypassed when required.

The cross-detector line can be evacuated separately through its dedicated vacuum-pump port before xenon is introduced. The ^{79}Kr source line will allow radioactive krypton to be added to the xenon flow during future calibration measurements. The system also retains connections to the small TPC and the $^{83\text{m}}\text{Kr}$ source. The different detector and source lines can be isolated using the valves in the system.

8.2 Integration of the Cross Detector

After assembly and the first commissioning tests of the PMTs installed in the cross detector, the detector was integrated into the existing GXe circulation system. The commissioning measurements are described in Chapter 9. Figure 34 shows the detector mounted in the experimental setup, while Figure 33 provides an overview of the complete gas system.

The detector was connected to the circulation loop using stainless-steel tubing and VCR metal-gasket face-seal fittings to provide leak-tight connections. During future operation, xenon will enter through one side of the gas-flow tube, pass through the active scintillation volume, and leave through the opposite side before returning to the circulation loop.

Purified xenon will flow continuously through the detector. The gas flow will be measured using the flow meter in the main circulation line, while the pressure will be measured using the pressure transducer installed at different positions in the system. The readings will be checked

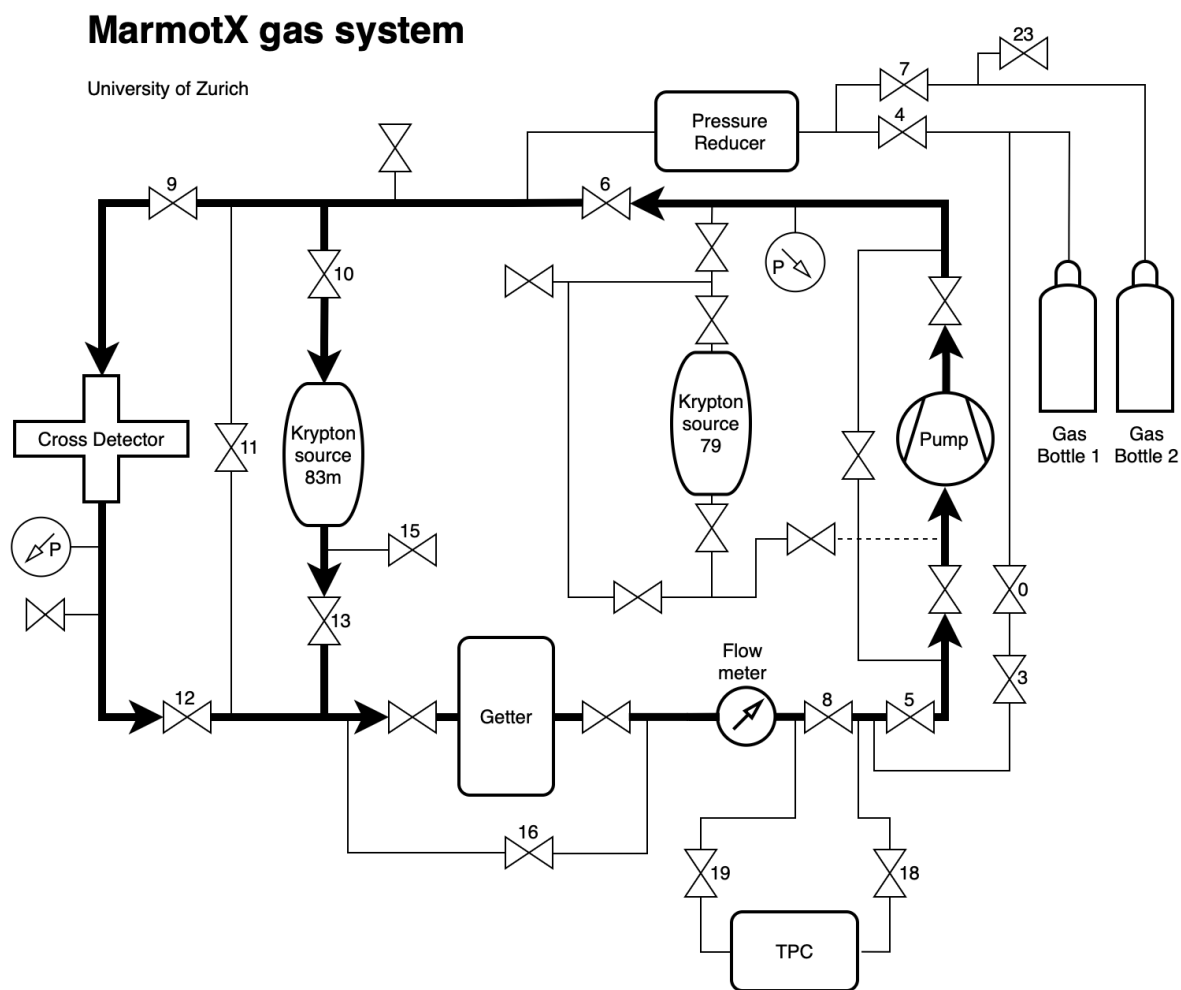


Figure 33: Schematic overview of the modified MarmotX gaseous xenon circulation system. The system includes the xenon supply, circulation pump, pump-bypass line, getter purifier, flow meter, pressure transducer, calibration-source lines, and the cross-detector line with its dedicated vacuum-pump port.

manually during operation. The integrated setup will also allow radioactive krypton from the $^{83\text{m}}\text{Kr}$ and ^{79}Kr source lines to be introduced into the circulation loop without changing the detector configuration.

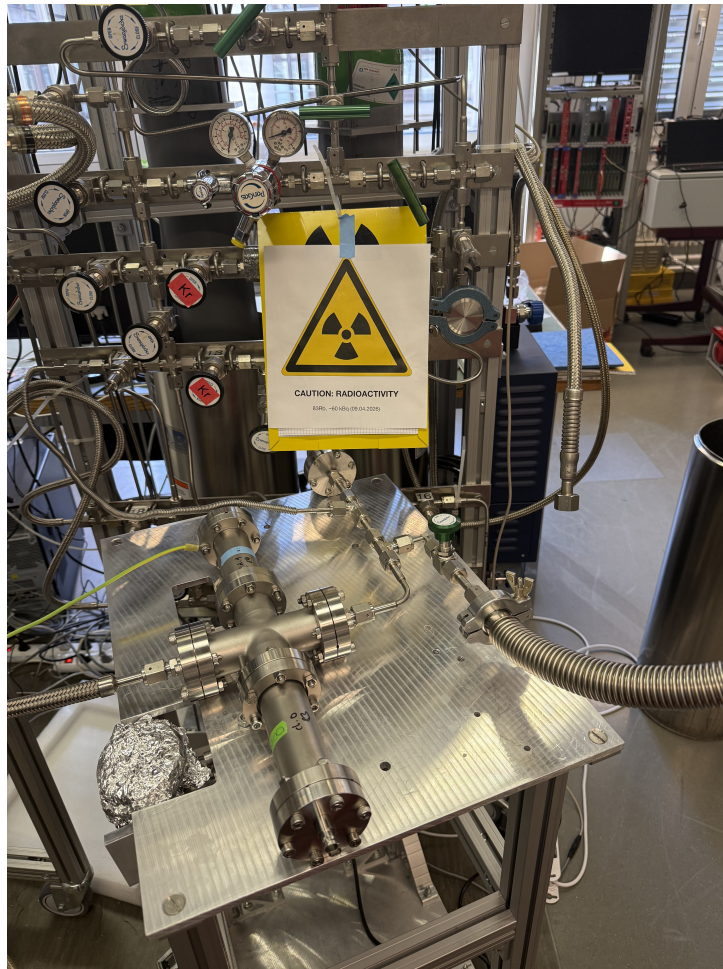


Figure 34: Photograph of the assembled cross detector after integration into the gaseous xenon circulation system. The detector is connected to the gas loop through stainless-steel tubing and VCR fittings.

9 First Commissioning Measurements

After the cross detector had been assembled, initial measurements were performed to test the detector and the readout and data acquisition system. As part of this commissioning, the dark-count rates of the two installed PMTs were measured. The first measurement was carried out in air, followed by a second measurement under vacuum.

The two installed PMTs were connected to the digitizer, with LV2483 connected to channel 0 and LV2480 connected to channel 1. Both PMTs were operated at a high-voltage of 800 V. The data were recorded using an external OR trigger, meaning that a signal in either PMT could trigger the data acquisition. This allowed for the dark-count rates of both PMTs to be measured individually.

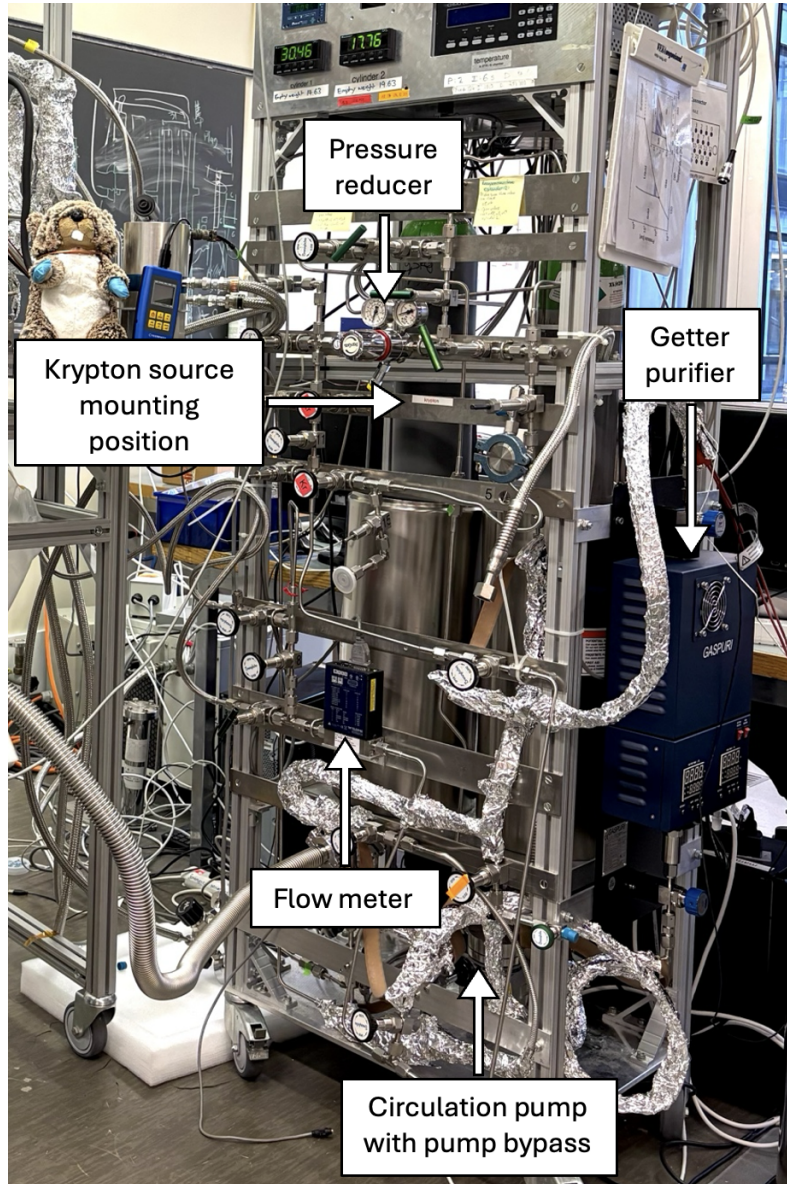


Figure 35: Photograph of the modified MarmotX gaseous xenon circulation system after the cross detector was integrated. The setup includes the xenon supply, circulation loop, getter purifier, monitoring instruments, and the integrated cross detector.

9.1 Dark-Count Analysis

The aim of the dark-count measurements was to study pulses recorded without an intentional light source. Besides dark counts from the PMTs themselves, the recorded signals may also contain electronic noise or pickup from the readout system. The measured rates therefore include all signal-like pulses that pass the pulse selection.

For each waveform, the baseline was first determined and subtracted. Pulse candidates were then identified using a threshold-based pulse finder. Once the waveform crossed the pulse-finder threshold, the start and end of the pulse were determined and an integration window was placed around it. The integrated pulse area A_{hit} was calculated by summing the baseline-corrected ADC samples within this window. If several pulse candidates were found in the same waveform, each pulse was treated as a separate hit.

9.1.1 Measurement in Air

The first dark-count measurement was performed in air at atmospheric pressure. At this stage, the detector was not yet connected to the gaseous xenon circulation system. The gas connections of the detector were sealed, and the detector was closed and light-tight during the measurement. In total, 500 000 events were recorded over a measurement time of 128 s. This measurement was performed shortly after the PMTs had been installed in the cross detector. It therefore also served as a first test of the fully assembled detector. In particular, it showed that both PMTs could be operated stably at 800 V without high-voltage discharges to the surrounding metallic detector components. It also confirmed that the PMTs and the readout system were correctly connected.

Figure 36 shows an example of the pulse-finding procedure after baseline subtraction. The pulse-finding threshold, pulse boundaries, and integration window are indicated in the figure. In this event, a pulse is found in the waveform of LV2480, while the waveform of LV2483 remains below the threshold. The pulse area was calculated for every identified hit. Figure 37 shows the

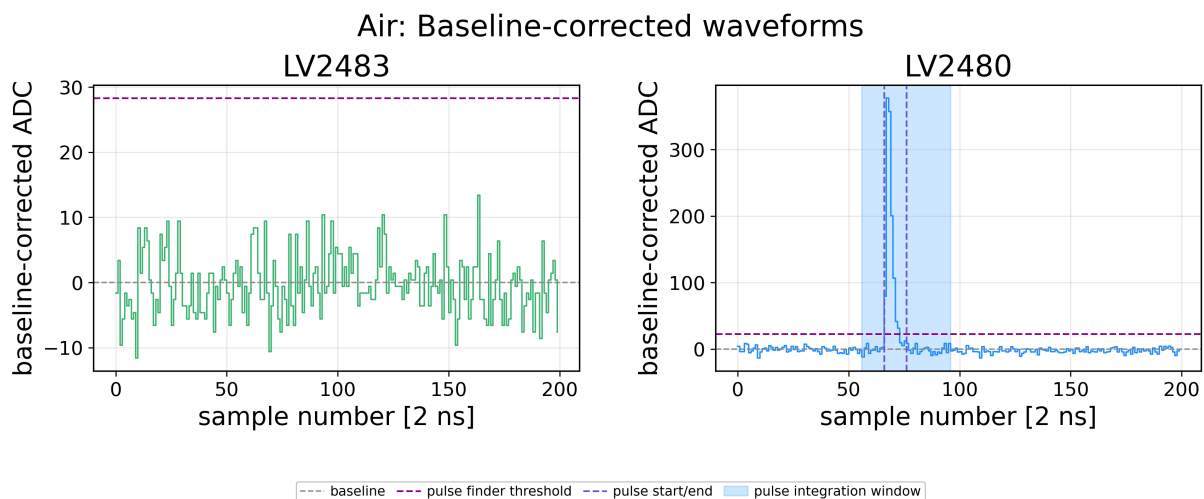


Figure 36: Example of baseline-corrected waveforms recorded in air. The pulse-finding threshold, pulse boundaries, and integration window are shown. A pulse is identified in LV2480, while the LV2483 waveform remains below the threshold.

resulting hit-area distributions for the two PMTs. Both distributions contain a broad population of positive pulse areas, but considerably more hits were recorded for LV2480 than for LV2483.

The distributions have different shapes at small pulse areas. A small positive DC voltage offset was present in the FAN IN/FAN OUT channel used for LV2480. Consequently, the nominal discriminator setting corresponded to a higher effective threshold than intended for this channel. Some small LV2480 pulses were therefore not recorded, producing the sharp cutoff visible on the low-area side of its distribution. The LV2483 channel was not affected to the same extent. The dark-count rate measured for LV2480 is therefore likely to be slightly underestimated relative to that of LV2483. Despite this reduced efficiency for small pulses, LV2480 still recorded considerably more hits than LV2483.

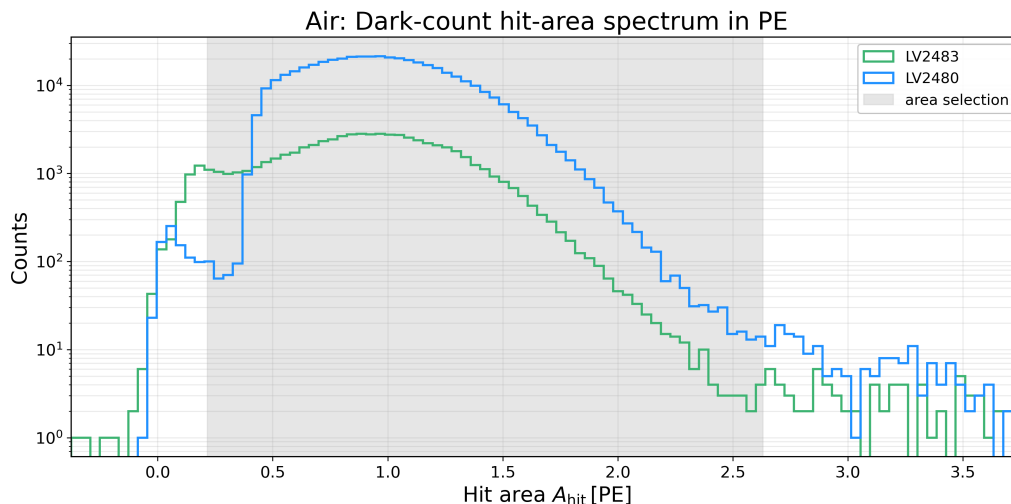


Figure 37: Hit-area distributions of LV2483 and LV2480 measured in air at atmospheric pressure. The different shapes at small pulse areas result from a DC voltage offset in the LV2480 readout channel, which increased its effective discriminator threshold. The shaded region marks the area range used to calculate the dark-count rates.

For the dark-count rate calculation, only hits within the area range

$$300 < A_{\text{hit}} < 3500 \quad (40)$$

were selected. This range was chosen to contain the broad single-photoelectron populations visible in the hit-area distributions. Intrinsic PMT dark counts are expected to originate predominantly from the thermionic emission of individual electrons from the photocathode or dynode system. After amplification by the PMT, these signals therefore have pulse areas close to the single-photoelectron response. The lower limit removes small signals close to the pulse-finding threshold, while the upper limit excludes the small number of large pulses outside the main population. The selected area range is marked by the shaded region in Figure 37.

Because the effective discriminator threshold was higher for LV2480, the selection efficiency close to the lower area boundary is not identical for the two PMTs. Pulses rejected by the discriminator cannot be recovered by the offline area selection. The comparison of the measured rates should therefore take into account that the LV2480 rate may be slightly underestimated.

The dark-count rate was calculated according to

$$R_{\text{DC}} = \frac{N_{\text{selected}}}{T}, \quad (41)$$

where N_{selected} is the number of hits within the selected area range and T is the duration of the measurement. Assuming Poisson statistics for the number of selected hits and neglecting the uncertainty in the measurement time, the statistical uncertainty of the rate is

$$\sigma_{R_{\text{DC}}} = \frac{\sqrt{N_{\text{selected}}}}{T}. \quad (42)$$

For LV2483, 62 011 hits passed the area selection, corresponding to a dark-count rate of

$$R_{\text{DC}}^{\text{LV2483}} = (484.5 \pm 1.9) \text{ Hz}. \quad (43)$$

LV2480 showed a much higher rate. In this case, 436 208 hits passed the area selection, giving

$$R_{\text{DC}}^{\text{LV2480}} = (3.408 \pm 0.005) \text{ kHz}. \quad (44)$$

The quoted uncertainties are statistical only and do not include the effect of the higher effective discriminator threshold in the LV2480 readout channel. The measured rate for LV2480 may therefore be slightly lower than the rate that would have been obtained with the intended threshold. No additional measurement without the DC offset was performed in this work.

9.1.2 Measurement under Vacuum

After the measurement in air, the detector was evacuated over a period of several days until a pressure of approximately 10^{-6} mbar was reached. The PMTs remained in darkness during this period. The dark-count measurement was then repeated under vacuum. Again, 500 000 events were recorded.

Because the data acquisition was triggered by PMT signals, the lower overall trigger rate observed under vacuum resulted in a longer measurement time. Recording 500 000 events under vacuum required 872 s, compared with 128 s for the measurement in air.

The vacuum data were analysed using the same baseline-correction and pulse-finding procedure as the data recorded in air. An example is shown in Figure 38. A pulse crossing the pulse-finding threshold is identified in LV2483. The pulse boundaries and corresponding integration window are indicated, while the waveform of LV2480 remains below the threshold.

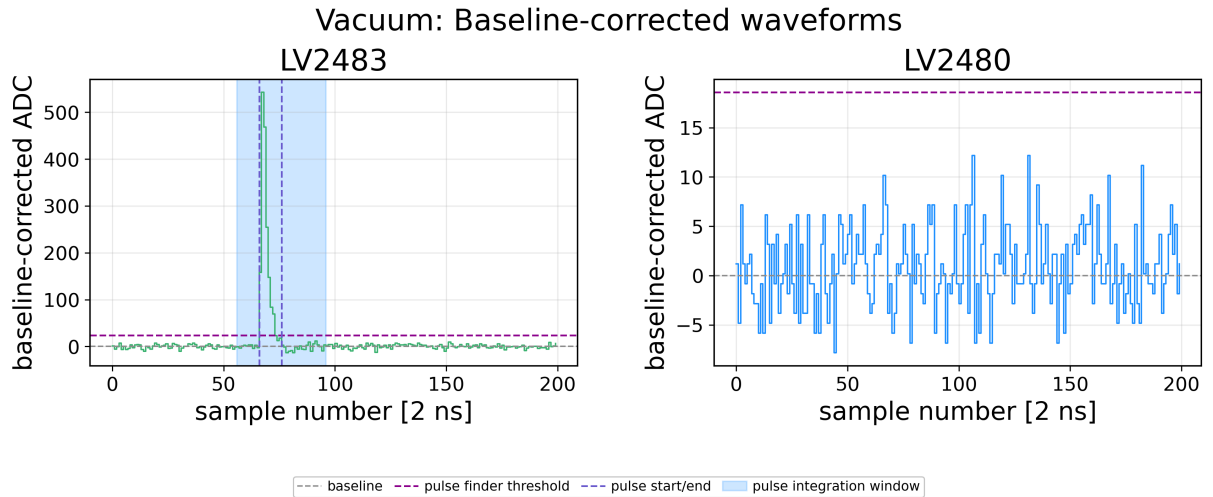


Figure 38: Example of baseline-corrected waveforms recorded under vacuum. A pulse is identified in LV2483, while the LV2480 waveform remains below the pulse-finding threshold. The pulse boundaries and integration window used to calculate the pulse area are indicated.

The hit-area distributions recorded under vacuum are shown in Figure 39. Compared with the measurement in air, the distributions of LV2483 and LV2480 are much closer in both shape

and number of hits. The same area range,

$$300 < A_{\text{hit}} < 3500, \quad (45)$$

was used for the rate calculation.

The readout configuration was unchanged between the measurements in air and under vacuum. The DC voltage offset in the LV2480 FAN IN/FAN OUT channel therefore also affected the vacuum measurement. As described for the measurement in air, the resulting increase in the effective discriminator threshold caused some small LV2480 pulses to be rejected. The dark-count rate measured for LV2480 under vacuum may therefore also be slightly underestimated.

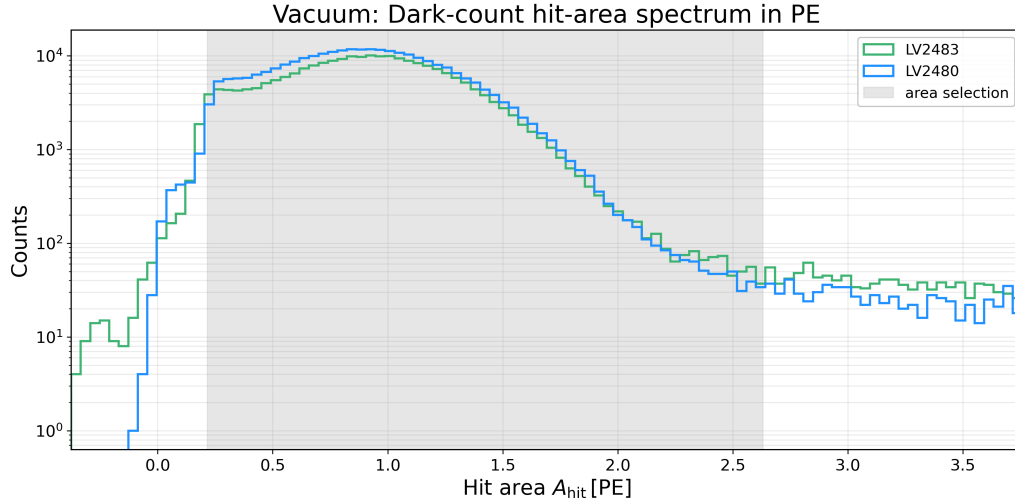


Figure 39: Hit-area distributions of LV2483 and LV2480 measured under vacuum at a pressure of approximately 10^{-6} mbar. The shaded region marks the area range used to calculate the dark-count rates. The higher effective discriminator threshold of the LV2480 readout channel reduces its efficiency for small pulses.

For LV2483, 223 768 hits passed the area selection. Using the same rate calculation and Poisson uncertainty introduced for the measurement in air gives

$$R_{\text{DC}}^{\text{LV2483}} = (256.6 \pm 0.5) \text{ Hz}. \quad (46)$$

For LV2480, 270 013 hits passed the area selection, corresponding to

$$R_{\text{DC}}^{\text{LV2480}} = (309.6 \pm 0.6) \text{ Hz}. \quad (47)$$

The quoted uncertainties are statistical only. They do not include the systematic effect caused by the higher effective discriminator threshold of the LV2480 readout channel. The measured LV2480 rate may therefore be slightly lower than the rate that would have been obtained with the intended discriminator threshold.

9.2 Dark-Count Results

The measured dark-count rates are summarized in Table 7, together with the statistical uncertainties calculated assuming Poisson statistics according to Equation 42.

The rates measured in air and under vacuum are compared in Figure 40. The figure shows the rates calculated from all identified hits as well as the rates obtained after applying the hit-area selection. The difference between the two is small for all measurements. Most identified

Condition	PMT	N_{selected}	R_{DC} [Hz]
Air	LV2483	62011	484.5 ± 1.9
Air	LV2480	436208	3407.9 ± 5.2
Vacuum	LV2483	223768	256.6 ± 0.5
Vacuum	LV2480	270013	309.6 ± 0.6

Table 7: Dark-count rates of LV2483 and LV2480 measured at an applied high voltage of 800 V. Only hits with $300 < A_{\text{hit}} < 3500$ were included in the rate calculation. The quoted uncertainties are statistical and were calculated assuming Poisson statistics for the number of selected hits.

hits therefore belong to the broad single-photoelectron population contained within the selected area range. This is consistent with a dominant contribution from single-electron-like pulses rather than from a large population of multi-photoelectron signals. However, the pulse-area distribution alone does not uniquely determine the origin of the recorded pulses.

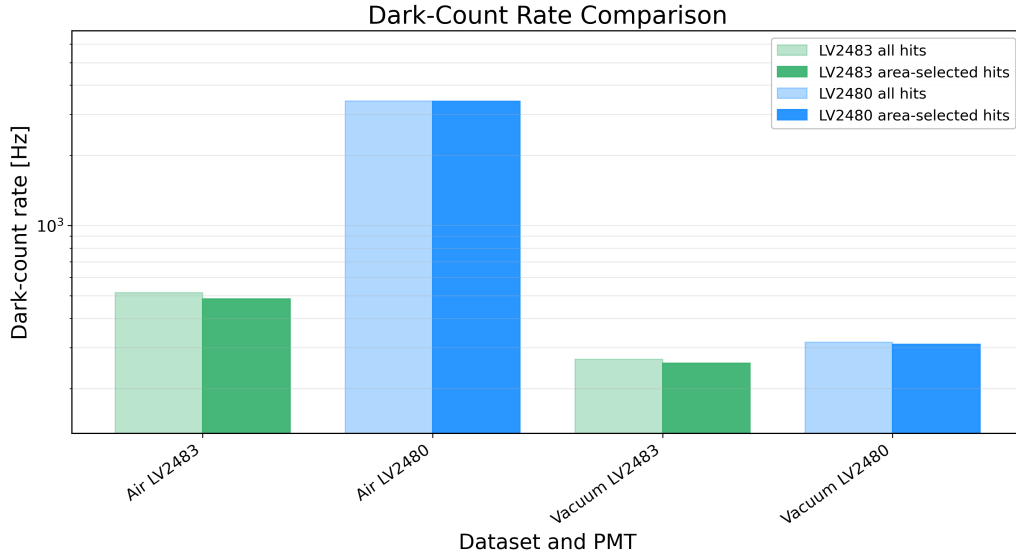


Figure 40: Dark-count rates of LV2483 and LV2480 measured in air and under vacuum. The rates obtained from all identified hits are compared with the rates after applying the hit-area selection.

A particularly large difference is seen for LV2480. Its measured dark-count rate decreases from (3.408 ± 0.005) kHz in air to (309.6 ± 0.6) Hz under vacuum. For LV2483, the rate decreases from (484.5 ± 1.9) Hz to (256.6 ± 0.5) Hz.

The rates measured under vacuum can also be compared with the manufacturer dark-current values listed in Table 1. To express the manufacturer values as equivalent single-photoelectron rates, the relation

$$R_{\text{eq}} = \frac{I_{\text{dark}}}{eG_{\text{Hamamatsu}}} \quad (48)$$

was used, where I_{dark} and $G_{\text{Hamamatsu}}$ are the dark current and gain at 800 V reported by Hamamatsu, respectively, and e is the elementary charge. This conversion assumes that each dark pulse produces an average anode charge corresponding to one photoelectron. The relative difference was calculated as

$$\Delta R = \frac{R_{\text{DC,vac}} - R_{\text{eq}}}{R_{\text{eq}}} \times 100\%. \quad (49)$$

The resulting equivalent rates and their comparison with the measured vacuum dark-count rates are summarized in Table 8. For both PMTs, the equivalent rates derived from the man-

PMT	I_{dark} [nA]	$G_{\text{Hamamatsu}}$	R_{eq} [Hz]	$R_{\text{DC,vac}}$ [Hz]	Difference
LV2480	0.24	4.1×10^6	365	310	-15.2 %
LV2483	0.17	3.7×10^6	287	257	-10.5 %

Table 8: Comparison of the equivalent single-photoelectron rates derived from the manufacturer dark-current and gain values with the dark-count rates measured under vacuum. The difference is expressed relative to the equivalent manufacturer rate.

ufacturer data are of the same order as the dark-count rates measured under vacuum. The measured rates are approximately 15 % lower for LV2480 and 11 % lower for LV2483. The relative ordering is also consistent: LV2480 has both the larger manufacturer dark current and the larger dark-count rate measured under vacuum.

This comparison is approximate because the manufacturer dark current may include leakage-current contributions and pulses with charges different from one photoelectron. Furthermore, the manufacturer and vacuum measurements were performed under different conditions, and the measured dark-count rate depends on the discriminator threshold and the selected pulse-area range. The higher effective discriminator threshold of the LV2480 readout channel may also cause its measured rate to be slightly underestimated.

The pressure itself is probably not the only reason for the difference between the rates measured in air and under vacuum. Previous PMT characterization studies have shown that the dark-count rate can remain elevated after ambient-light exposure and that several hours in darkness may be required for the rate to stabilize [26].

Several days passed between the air and vacuum measurements because the detector first had to be pumped down to a pressure of approximately 10^{-6} mbar. The PMTs remained in darkness during this time. The lower rates measured under vacuum may therefore partly result from the longer time spent in darkness and not only from the change in pressure. For this reason, the vacuum measurement should provide a better estimate of the dark-count rates during later detector operation. No second vacuum measurement was performed at a later time to test the reproducibility of the measured rates.

The vacuum dark-count rates measured in this work, approximately 257 Hz for LV2483 and 310 Hz for LV2480, are comparable to the average random PMT rate of approximately 0.3 kHz reported for R8520-406 PMTs operated in gaseous xenon at room temperature [27]. During operation in liquid xenon, the same study reported a lower average rate of approximately 0.06 kHz. A direct comparison is limited by differences in temperature, detector environment, pulse threshold, and analysis method.

For operation at approximately -100°C , the dark-count rates are expected to be lower than the room-temperature vacuum rates measured in this work because thermionic emission decreases at lower temperatures.

A possible additional contribution during the air measurement is scintillation light produced when ionizing radiation excites or ionizes molecules in the air. This light originates mainly from excited nitrogen molecules, N_2 , and nitrogen molecular ions, N_2^+ , which emit photons when returning to lower-energy states. Such events may produce larger signals than ordinary thermionic dark counts, which are concentrated around the single-photoelectron region. [28]

To investigate the pulse-area populations, the hit areas were converted to photoelectron equivalents using the measured gain of each PMT. The resulting spectra are shown in Figure 41.

For both PMTs, the main pulse population is found close to 1 PE. The peak positions are approximately 0.89 PE for both PMTs in air. Under vacuum, the peaks are located at approximately 0.95 PE for LV2483 and 0.90 PE for LV2480. The large number of additional pulses

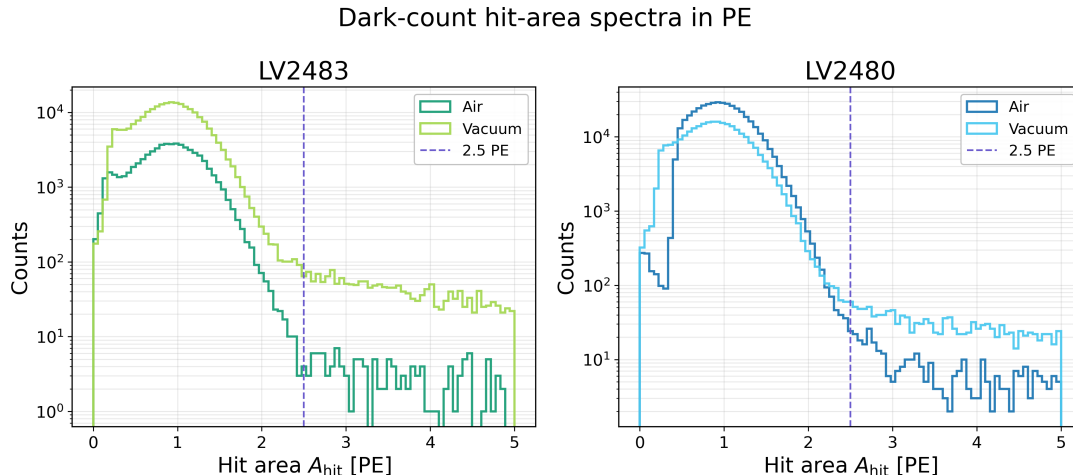


Figure 41: Hit-area spectra of LV2483 and LV2480 measured in air and under vacuum. The hit areas were converted to photoelectron equivalents using the measured gain of each PMT.

recorded by LV2480 in air is therefore concentrated around the single-photoelectron region. This is consistent with an increased dark count component after the PMT had previously been exposed to ambient light.

To compare the occurrence of larger pulses without the result being dominated by the different total single-photoelectron rates, a more conservative area threshold of 2.5 PE was applied. This threshold lies above the main single-photoelectron population and is therefore less sensitive to small differences in gain calibration or to the high-area tail of the single-photoelectron distribution. The absolute rate of pulses with an area of at least 2.5 PE was calculated as

$$R_{\geq 2.5 \text{ PE}} = \frac{N(A_{\text{hit}} \geq 2.5 \text{ PE})}{T}. \quad (50)$$

The statistical uncertainty was again calculated assuming Poisson statistics,

$$\sigma_{R_{\geq 2.5 \text{ PE}}} = \frac{\sqrt{N(A_{\text{hit}} \geq 2.5 \text{ PE})}}{T}. \quad (51)$$

The resulting numbers and rates are summarized in Table 9 and shown in Figure 42.

Condition	PMT	$N(A_{\text{hit}} \geq 2.5 \text{ PE})$	$R_{\geq 2.5 \text{ PE}} \text{ [Hz]}$
Air	LV2483	254	1.98 ± 0.12
Air	LV2480	637	4.98 ± 0.20
Vacuum	LV2483	4094	4.69 ± 0.07
Vacuum	LV2480	2782	3.19 ± 0.06

Table 9: Numbers and absolute rates of identified pulses with an integrated area of at least 2.5 PE for measurements in air and under vacuum. The rates were calculated using measurement durations of 128 s in air and 872 s under vacuum. The quoted uncertainties are statistical.

The absolute large-pulse rates show different trends for the two PMTs. For LV2483, the rate decreases from (4.69 ± 0.07) Hz under vacuum to (1.98 ± 0.12) Hz in air. In contrast, the LV2480 rate increases from (3.19 ± 0.06) Hz under vacuum to (4.98 ± 0.20) Hz in air.

A contribution from scintillation light produced in the common detector volume would be expected to produce approximately coincident pulses in both PMTs. The opposite trends observed for LV2483 and LV2480 therefore do not provide consistent evidence for an additional

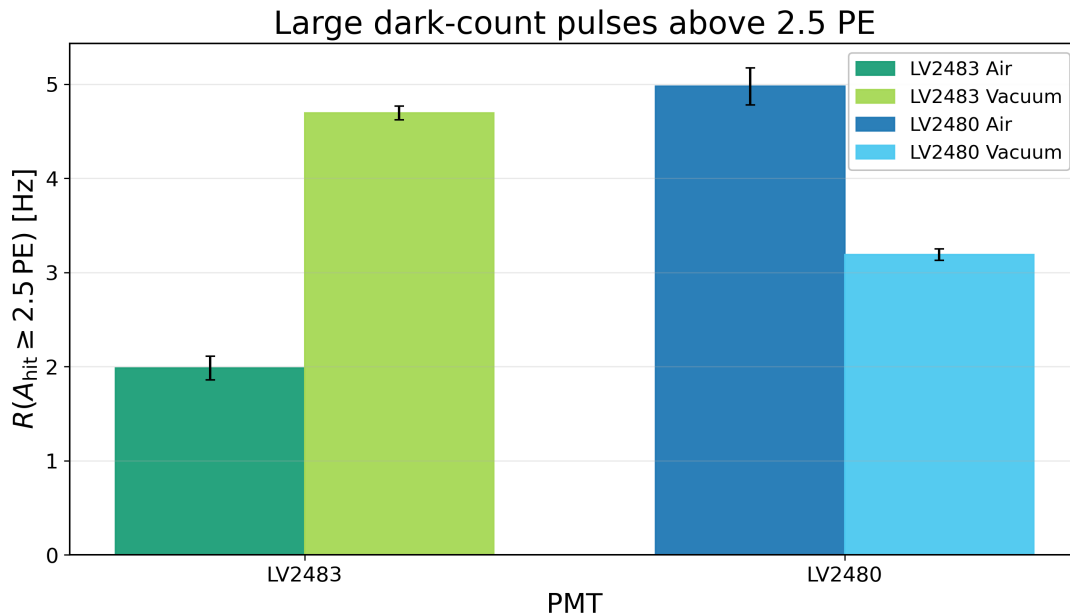


Figure 42: Absolute rates of identified dark-count pulses with an integrated area of at least 2.5 PE for LV2483 and LV2480 measured in air and under vacuum. The error bars show the statistical uncertainties calculated assuming Poisson statistics.

scintillation-light population in air. The difference observed for LV2480 alone may instead be affected by PMT-specific dark noise or by the different effective discriminator thresholds of the two readout channels. A contribution from scintillation light in air cannot be excluded from these measurements, but it cannot be identified conclusively.

The much larger difference between the air and vacuum measurements is found around the single-photoelectron region. LV2480 records a large number of additional pulses close to 1 PE in air. Since the air measurement was performed shortly after the PMTs had been installed and exposed to ambient light, the previous light exposure is a likely explanation for the elevated rate. This cannot be confirmed from the two measurements alone. A dedicated measurement of the dark-count rate as a function of time after controlled light exposure would be required to investigate this effect in more detail.

The air measurement was nevertheless an important part of the detector commissioning. It was the first measurement with the PMTs installed in their final positions in the cross detector. Both PMTs could be operated stably at 800 V, and no high-voltage discharges to the surrounding metallic detector components were observed. The measurement also confirmed that both PMTs were correctly connected and could be read out. These checks were performed before the detector was pumped down and leak checked.

Since intrinsic dark pulses in the two PMTs occur independently, a coincidence requirement can reject most single-PMT dark counts. However, two independent dark pulses may occasionally occur within the same coincidence window. The expected accidental-coincidence rate is

$$R_{\text{acc}} = R_{\text{LV2483}} R_{\text{LV2480}} \Delta t, \quad (52)$$

where Δt is the full allowed time separation between the two pulses. Using the rates measured under vacuum gives

$$\begin{aligned}
R_{\text{acc}} &= (256.6 \text{ Hz})(309.6 \text{ Hz})\Delta t \\
&\approx 0.080 \text{ Hz} \left(\frac{\Delta t}{1 \mu\text{s}} \right).
\end{aligned} \tag{53}$$

The recorded waveforms contain approximately 200 samples with a sampling interval of 2 ns, corresponding to a total waveform duration of approximately 400 ns. Using the full waveform duration as a conservative coincidence window gives

$$R_{\text{acc}} \approx 0.032 \text{ Hz}, \tag{54}$$

corresponding to approximately one accidental coincidence every 31 s. This is a conservative estimate because the coincidence window used in the event analysis can be chosen much narrower than the full waveform. Pulse-area requirements will further reduce the accidental background.

Accidental coincidences can imitate an event observed by both PMTs and may therefore contribute to the background in future ^{79}Kr measurements. Their importance will depend on the expected source-event rate, the final coincidence window, and the pulse-area selection. The value calculated above is also based on the measured LV2480 dark-count rate, which may be slightly underestimated because of its higher effective discriminator threshold.

Part IV

Conclusions and Outlook

10 Conclusions

The aim of this thesis was to prepare a small gaseous xenon detector for future measurements with ^{79}Kr . The work was divided into two main parts. First, suitable photomultiplier tubes were characterized and selected. In the second part, the selected PMTs were installed in the cross detector, which was assembled, commissioned, and integrated into the existing xenon gas system.

For the PMT characterization, four Hamamatsu R8520 PMTs were investigated in detail. The PMTs were selected based on the information provided by Hamamatsu and were then studied using gain and afterpulse measurements. The gain measurements were performed at high voltages between 700 V and 900 V. For all four PMTs, the gain increased with increasing high voltage, as expected from the electron multiplication in the dynode chain. The measured gain values at 800 V were also compared with the values calculated from the Hamamatsu final test sheets. The results were in a similar gain range, although some differences between the measured and provided values were observed.

The existing gain analysis was extended during this thesis. In addition to the model-independent gain calculation, a model-dependent fit of the integrated charge spectra was implemented. This made it possible to determine the gain from the separation between the pedestal and the single-photoelectron peak. The fit also provided information about the width of the single-photoelectron distribution. At higher operating voltages, the pedestal and photoelectron contributions became more clearly separated and the relative SPE width decreased. The model-dependent method was used for the final gain values, while the model-independent method served as a cross-check and provided initial values for the charge-spectrum fits.

The afterpulse behaviour of the four PMTs was investigated at an applied high voltage of 800 V. For this analysis, the existing afterpulse code was modified and extended to better treat the recorded PMT waveforms. In particular, additional criteria were introduced to separate neighbouring afterpulse signals, avoid double counting of merged pulses, and suppress small ringing structures close to the main PMT pulse.

The afterpulse measurements showed larger differences between the individual PMTs than the gain measurements. For all investigated PMTs, most afterpulse signals had pulse areas below 2 PE and appeared at relatively short delay times after the main pulse. LV2483 showed the lowest total afterpulse rate of the four investigated PMTs, while LV2485 showed a considerably higher rate. LV2480 and LV2481 showed intermediate values. The differences in the total afterpulse rates were mainly caused by the number of small afterpulse signals below 2 PE.

Based on the combined gain and afterpulse results, PMTs LV2480 and LV2483 were selected for the cross detector. Both PMTs showed stable gain behaviour over the investigated voltage range. Their gain values were also similar, which is useful when two PMTs are used to observe the same detector volume. In addition, both PMTs showed comparatively low afterpulse rates, with LV2483 having the lowest measured rate of all investigated tubes.

The two selected PMTs were then installed in the cross detector. The detector consists of stainless-steel components arranged in a cross-shaped geometry, with the two PMTs positioned opposite each other. In this configuration, both PMTs observe the same gaseous xenon volume. After assembly, the first commissioning measurements were performed in air and under vacuum. The cross detector was then integrated into the xenon gas system, which will allow purified xenon to circulate through the detector while the pressure and gas flow are monitored.

During the commissioning measurements, the dark-count rates of the two installed PMTs were measured at an applied high voltage of 800 V. In air, dark-count rates of approximately 484 Hz and 3.41 kHz were measured for LV2483 and LV2480, respectively. Under vacuum, the measured rates decreased to approximately 257 Hz for LV2483 and 310 Hz for LV2480. In particular, the large change observed for LV2480 indicates that the high rate measured in air was likely not caused by the intrinsic dark-count rate of the PMT alone. A possible explanation is a temporary increase of the dark-count rate after previous exposure of the PMT to ambient light, for example due to delayed light emission from PMT materials. Additional contributions from the measurement conditions or from scintillation processes in air cannot be fully excluded.

Under vacuum, the dark-count rates of the two PMTs were much closer and both were of the order of a few hundred hertz. The investigation of the pulse-area spectra showed that the additional pulses measured in air were mainly concentrated around the single-photoelectron region. The absolute rate of pulses above 2.5 PE did not show a consistent increase in both PMTs, so no clear common scintillation-light population in air was identified. A contribution from nitrogen scintillation cannot be excluded, but no clear evidence for it was found in these measurements. Nitrogen scintillation is emitted mainly in the near-ultraviolet region between approximately 300 nm and 430 nm, with a strong emission band at about 337 nm. [28]

The commissioning measurements confirmed the operation of both PMTs after their installation and provided a first test of the detector and readout system in the assembled configuration. Both PMTs could be operated stably at 800 V, and no high-voltage discharges to the surrounding metallic detector components were observed. The measured dark-count rates also support the use of a coincidence between the two PMTs mounted opposite each other to suppress uncorrelated pulses during future scintillation measurements.

Overall, the work carried out in this thesis provides the PMT characterization and selection, the assembled cross detector, and the analysis methods needed for the next measurements with radioactive krypton calibration sources. This is an important preparatory step towards studying ^{79}Kr as a possible internal calibration source for liquid xenon detectors.

Such calibration sources are especially relevant for future large-scale detectors, where external sources are limited by the strong self-shielding of liquid xenon. Since ^{79}Kr can be distributed inside the detector volume and produces decay signatures related to multi-site event topologies, it is a promising tool for studying event reconstruction, spatial response, and cluster identification. These detector properties are important for searches for the two-neutrino and neutrinoless electron-capture with positron-emission modes of ^{124}Xe , $2\nu\text{EC}\beta^+$ and $0\nu\text{EC}\beta^+$, whose characteristic multi-site signatures have to be reconstructed reliably.

11 Outlook

As a first indication of the measurements that can be performed with the completed setup, Figure 43 shows an example waveform from a $^{83\text{m}}\text{Kr}$ measurement with the cross detector. A larger first pulse followed by a smaller second pulse can be seen. These could be related to the 32.1 keV and 9.4 keV transitions of the $^{83\text{m}}\text{Kr}$ decay cascade, which are separated by an intermediate state with a half-life of about 157 ns. A more detailed analysis would be needed to confirm this interpretation. The example nevertheless gives a first impression of the type of signals that can be observed with the cross detector.

Further measurements with $^{83\text{m}}\text{Kr}$ can be used to test the detector response and the operation of the complete setup with a well-known radioactive source. The source can be introduced into the xenon circulation and transported through the cross detector, where the scintillation light from its decays is detected by the two opposing PMTs. These measurements can also be used

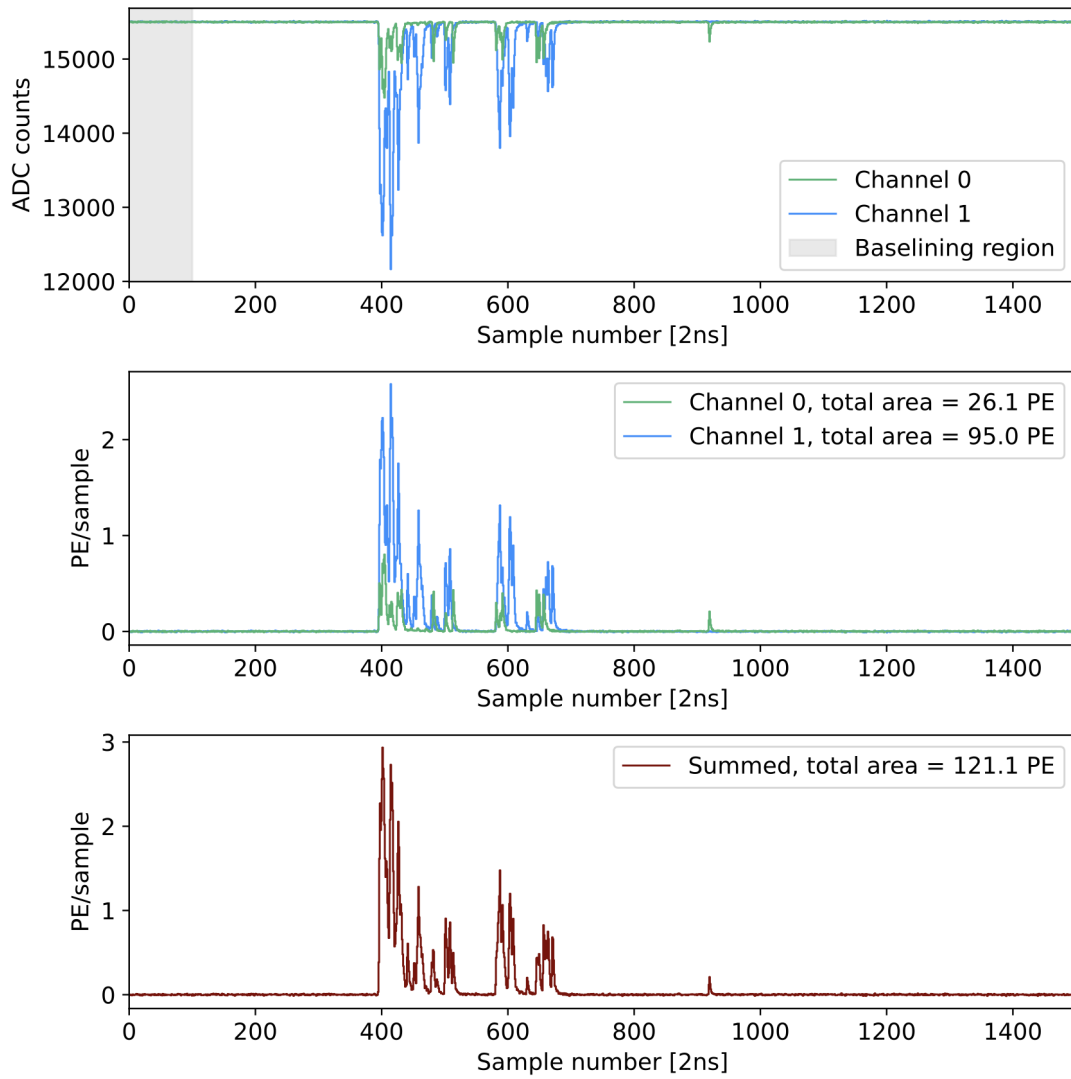


Figure 43: Example waveform from a $^{83\text{m}}\text{Kr}$ measurement with the cross detector. The upper panel shows the raw waveforms of both PMTs, the middle panel shows the baseline-subtracted waveforms converted to photoelectrons, and the lower panel shows the summed waveform. A larger first pulse followed by a smaller second pulse can be seen, which could be related to the 32.1 keV and 9.4 keV transitions of the $^{83\text{m}}\text{Kr}$ decay cascade. Figure produced and provided by Luisa Höttsch.

to study the response of both PMTs to the same events and to further test the gas circulation and source injection procedure.

After these commissioning measurements, ^{79}Kr will be introduced into the cross detector using the same gas circulation and source injection system. This will allow the scintillation signals from ^{79}Kr decays to be studied in gaseous xenon. The measured pulse areas, signal shapes, and distributions can then be compared between the two PMTs.

A further step will be the characterization of the ^{79}Kr source in the detector. This will include studying signals from the different decay branches and measuring the source activity over time. The measurements can also be used to better understand the transport and distribution of ^{79}Kr in the xenon gas system.

In the future, a small liquid xenon TPC is planned to be integrated into the gas system together with the cross detector. The experience gained from the cross-detector measurements and from the handling of the ^{79}Kr source can then be transferred to measurements in liquid xenon. This will allow ^{79}Kr to be studied under conditions closer to those in larger liquid xenon detectors.

The cross detector therefore provides an intermediate step between the source production and future measurements in a liquid xenon TPC. The measurements with $^{83\text{m}}\text{Kr}$ and later ^{79}Kr will help to test the source handling, detector response, and reconstruction of the resulting signals. In the longer term, these studies contribute to the development of new internal calibration methods for large liquid xenon detectors, especially for measurements where multi-site event topologies are important.

Part V

Appendix

A Gain Plots

This section contains the gain measurement results for all investigated PMTs at the different applied high voltages. The corresponding analysis and discussion are presented in the main text.

A.1 LV2480

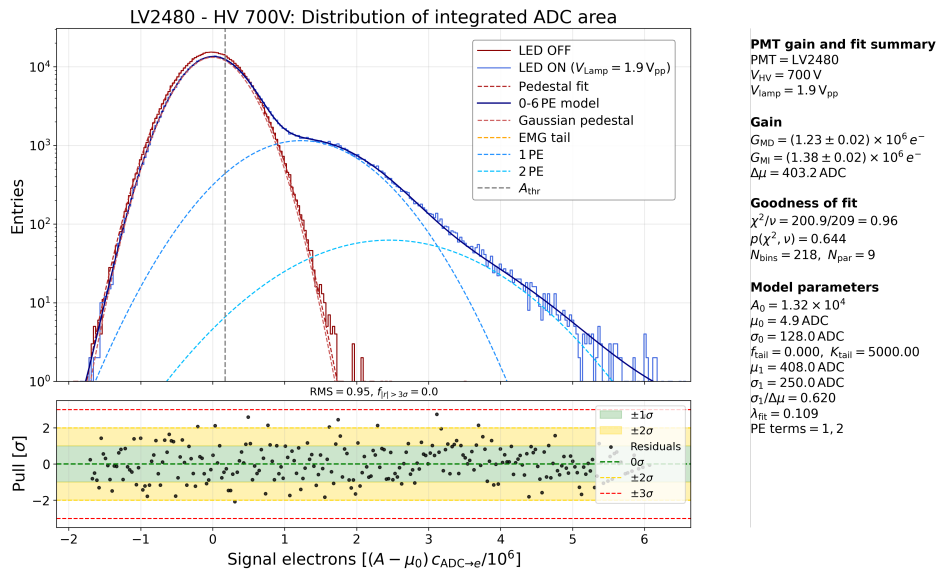


Figure 44: Integrated charge spectrum of PMT LV2480 measured at an applied high voltage of 700 V. The fitted model components and the pull residuals are shown.

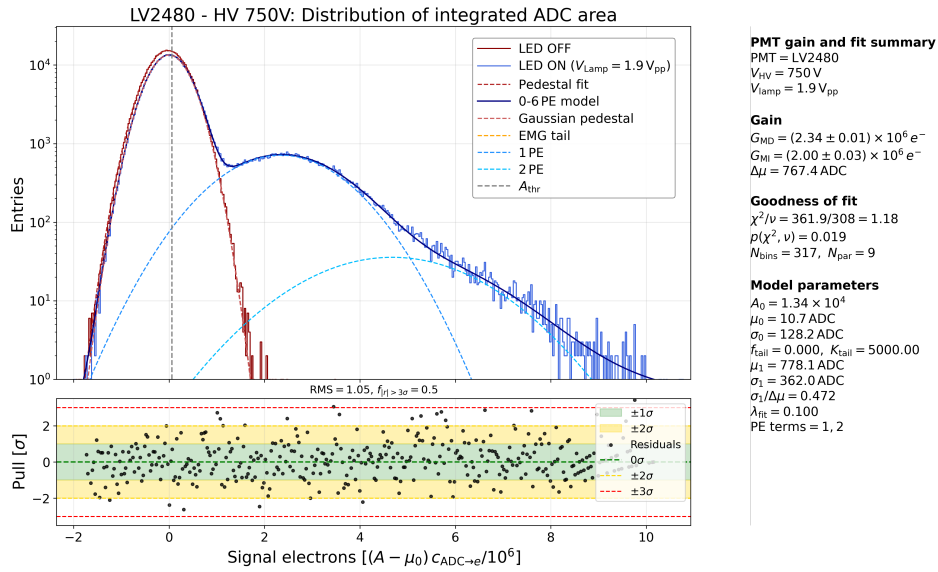


Figure 45: Integrated charge spectrum of PMT LV2480 measured at an applied high voltage of 750 V. The fitted model components and the pull residuals are shown.

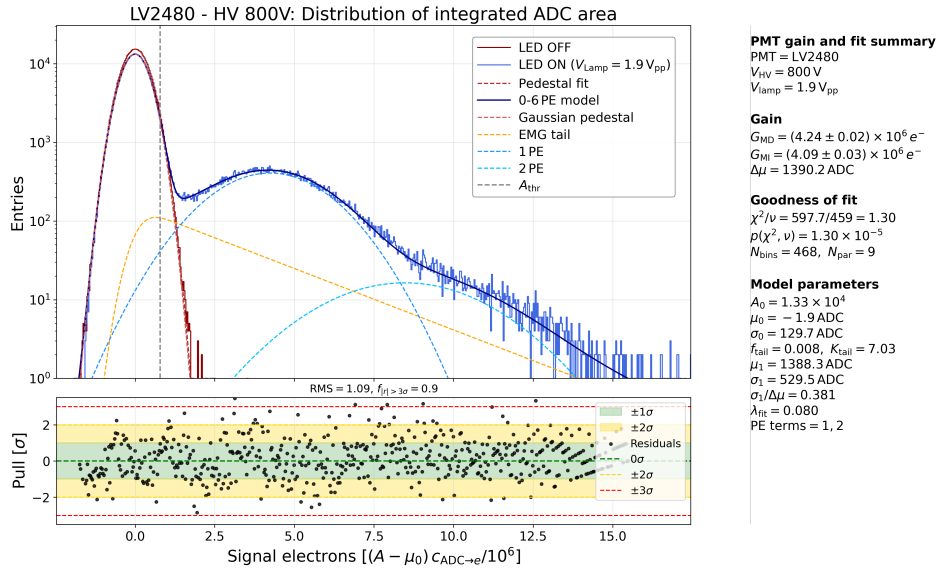


Figure 46: Integrated charge spectrum of PMT LV2480 measured at an applied high voltage of 800 V. The fitted model components and the pull residuals are shown.

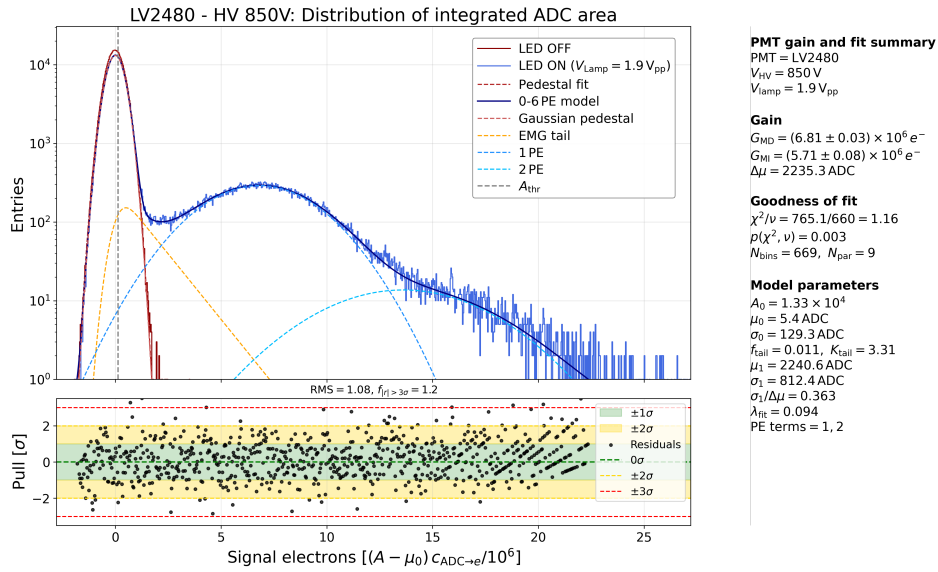


Figure 47: Integrated charge spectrum of PMT LV2480 measured at an applied high voltage of 850 V. The fitted model components and the pull residuals are shown.

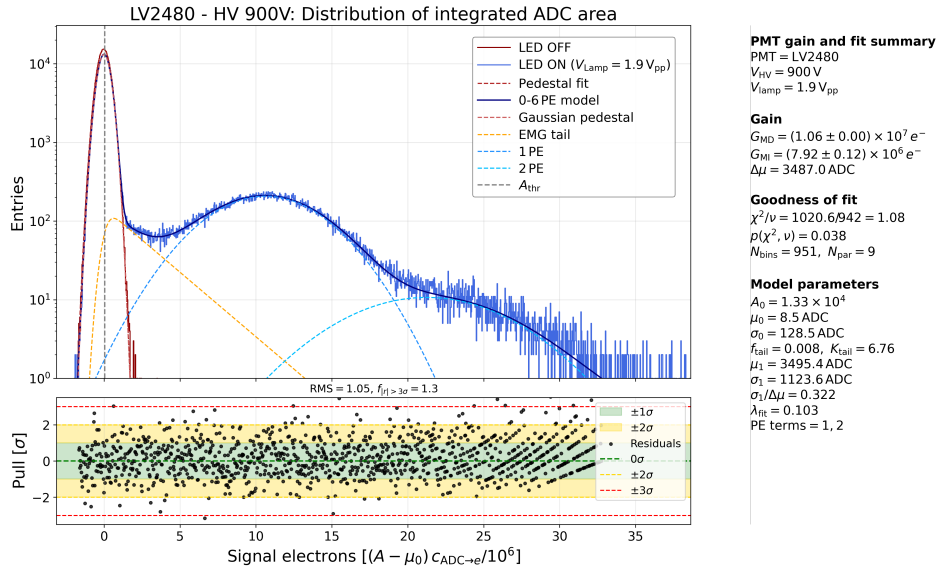


Figure 48: Integrated charge spectrum of PMT LV2480 measured at an applied high voltage of 900 V. The fitted model components and the pull residuals are shown.

A.2 LV2481

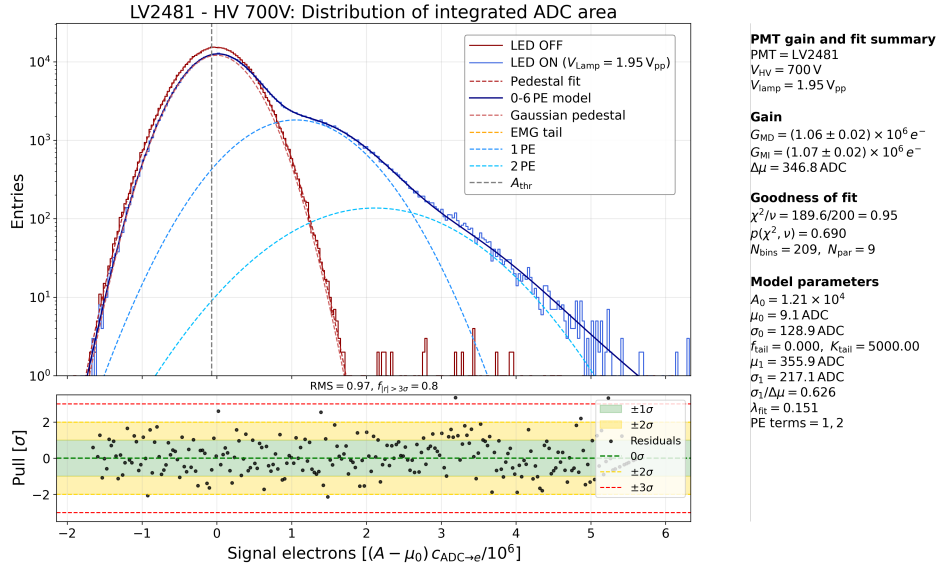


Figure 49: Integrated charge spectrum of PMT LV2481 measured at an applied high voltage of 700 V. The fitted model components and the pull residuals are shown.

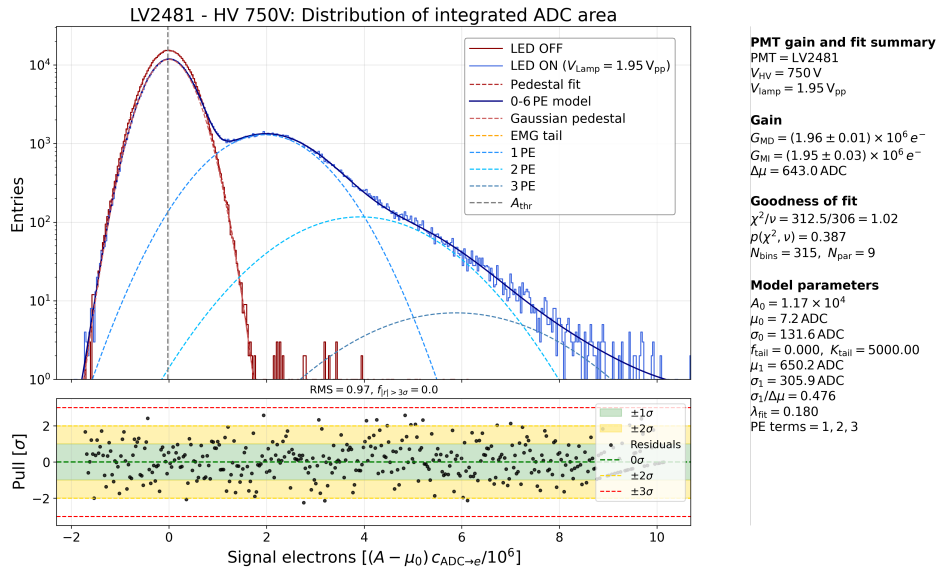


Figure 50: Integrated charge spectrum of PMT LV2481 measured at an applied high voltage of 750 V. The fitted model components and the pull residuals are shown.

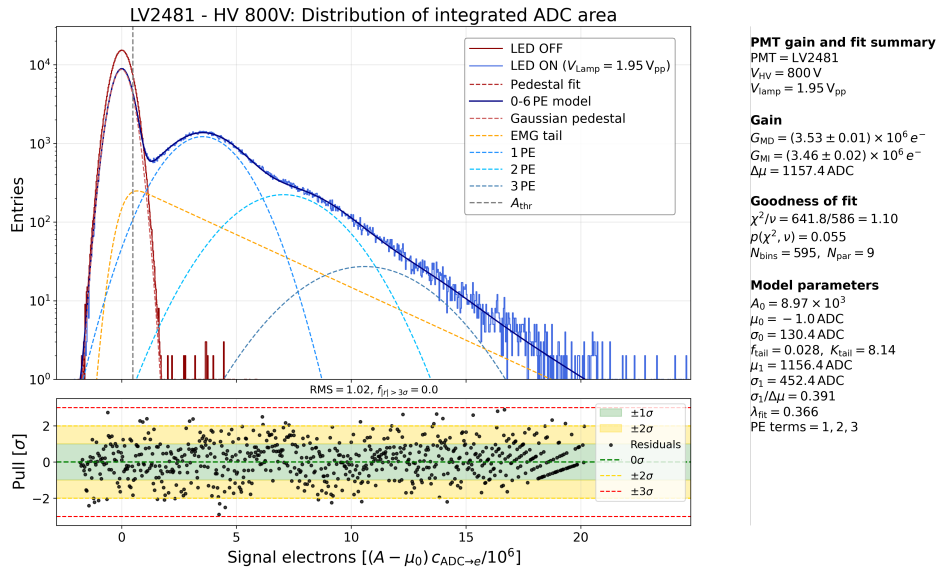


Figure 51: Integrated charge spectrum of PMT LV2481 measured at an applied high voltage of 800 V. The fitted model components and the pull residuals are shown.

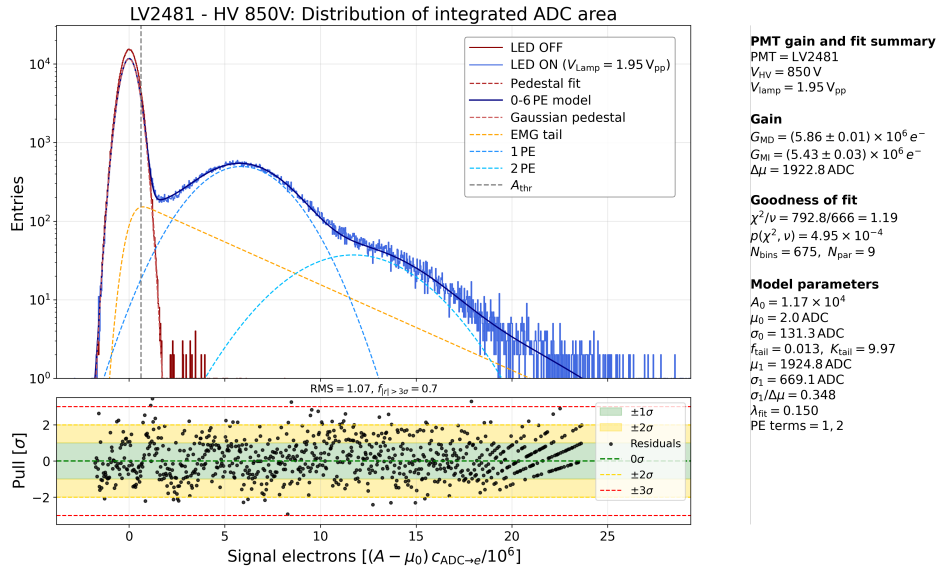


Figure 52: Integrated charge spectrum of PMT LV2481 measured at an applied high voltage of 850 V. The fitted model components and the pull residuals are shown.

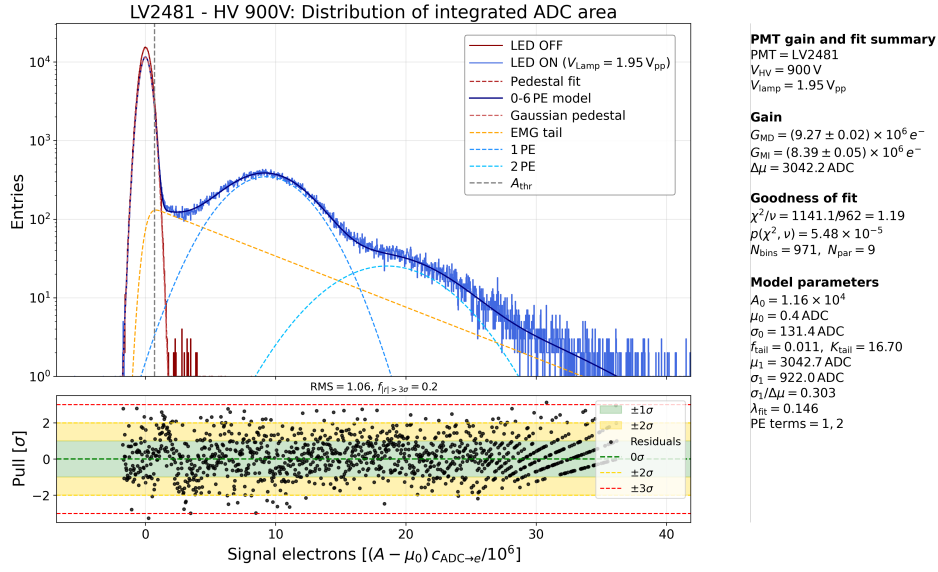


Figure 53: Integrated charge spectrum of PMT LV2481 measured at an applied high voltage of 900 V. The fitted model components and the pull residuals are shown.

A.3 LV2483

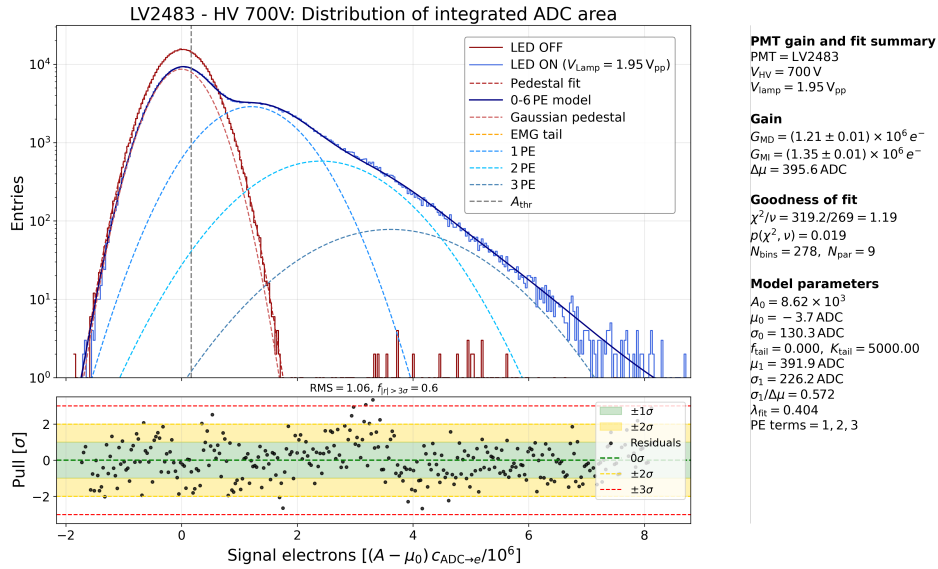


Figure 54: Integrated charge spectrum of PMT LV2483 measured at an applied high voltage of 700 V. The fitted model components and the pull residuals are shown.

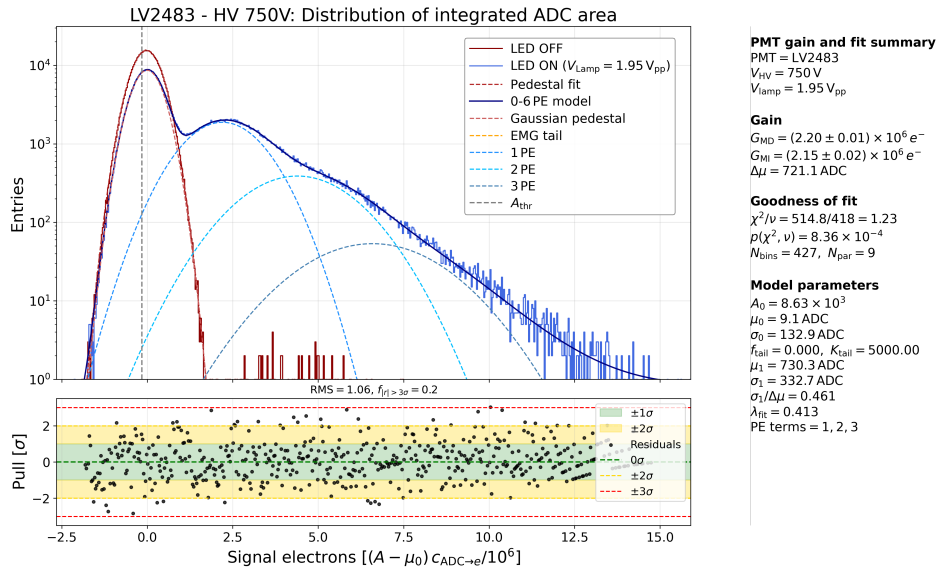


Figure 55: Integrated charge spectrum of PMT LV2483 measured at an applied high voltage of 750 V. The fitted model components and the pull residuals are shown.

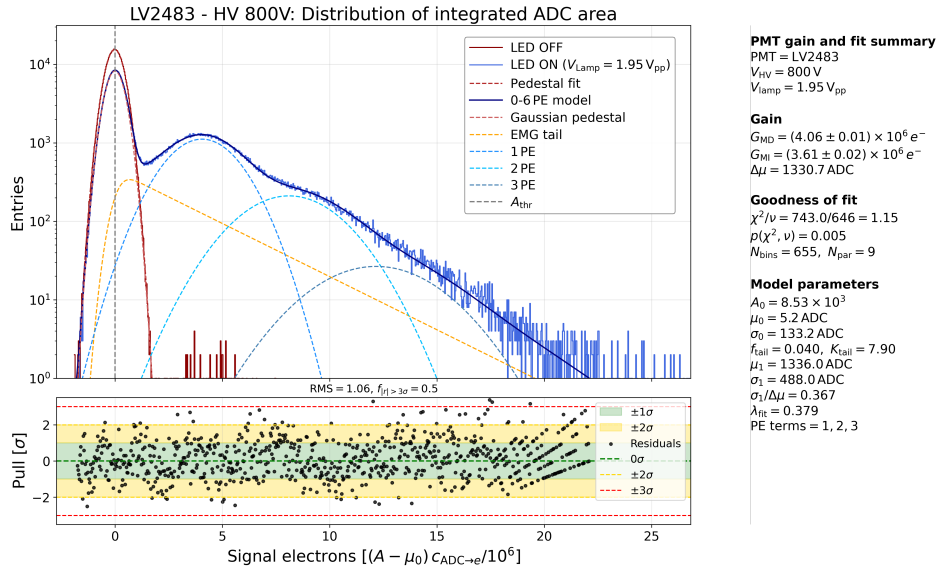


Figure 56: Integrated charge spectrum of PMT LV2483 measured at an applied high voltage of 800 V. The fitted model components and the pull residuals are shown.

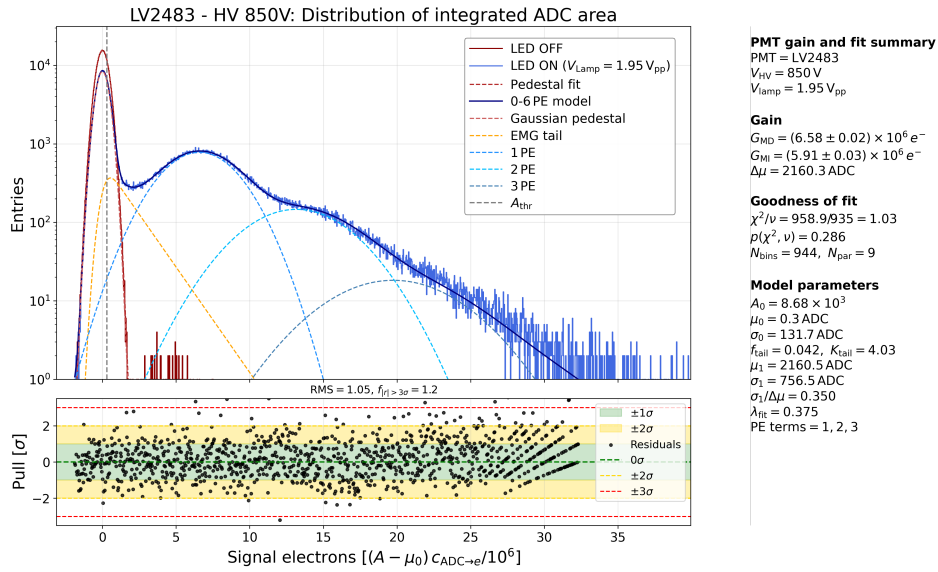


Figure 57: Integrated charge spectrum of PMT LV2483 measured at an applied high voltage of 850 V. The fitted model components and the pull residuals are shown.

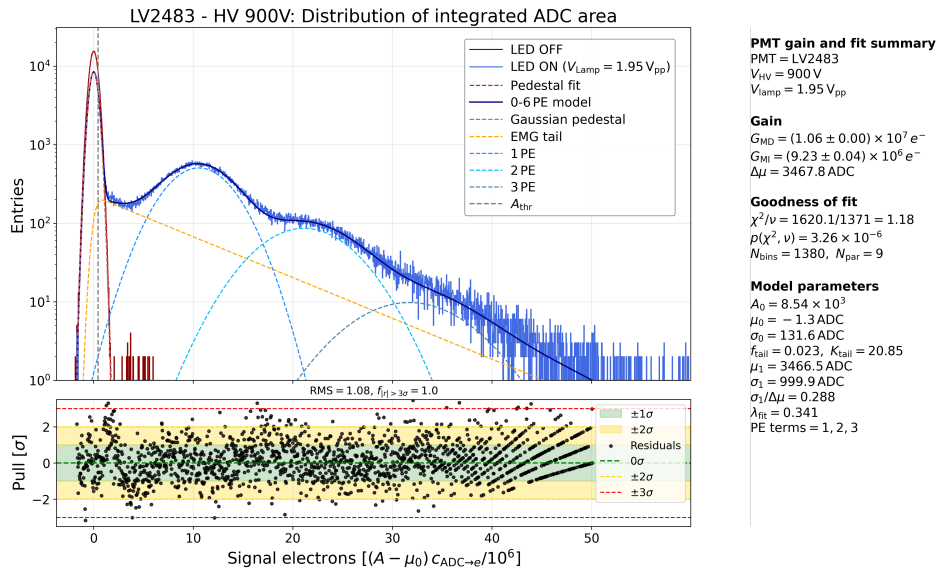


Figure 58: Integrated charge spectrum of PMT LV2483 measured at an applied high voltage of 900 V. The fitted model components and the pull residuals are shown.

A.4 LV2485

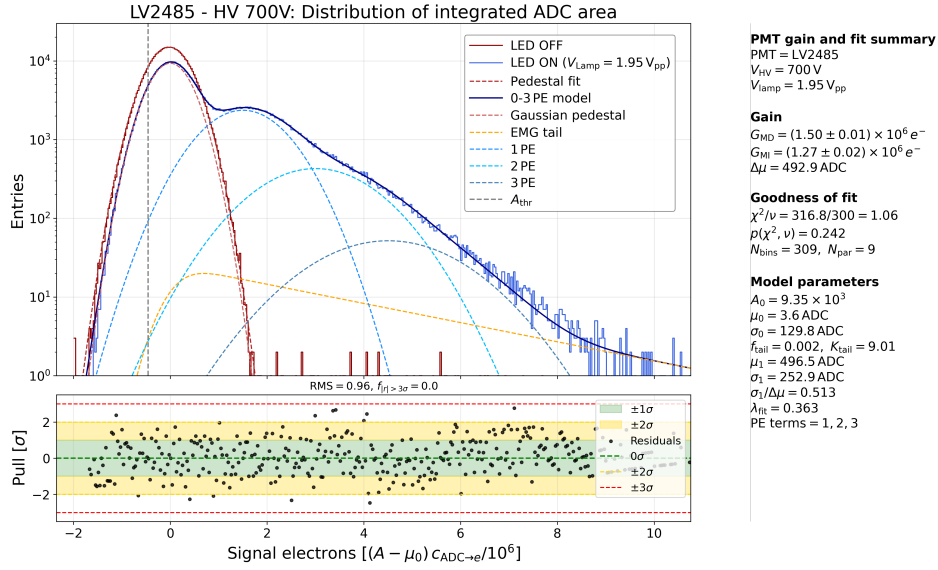


Figure 59: Integrated charge spectrum of PMT LV2485 measured at an applied high voltage of 700 V. The fitted model components and the pull residuals are shown.

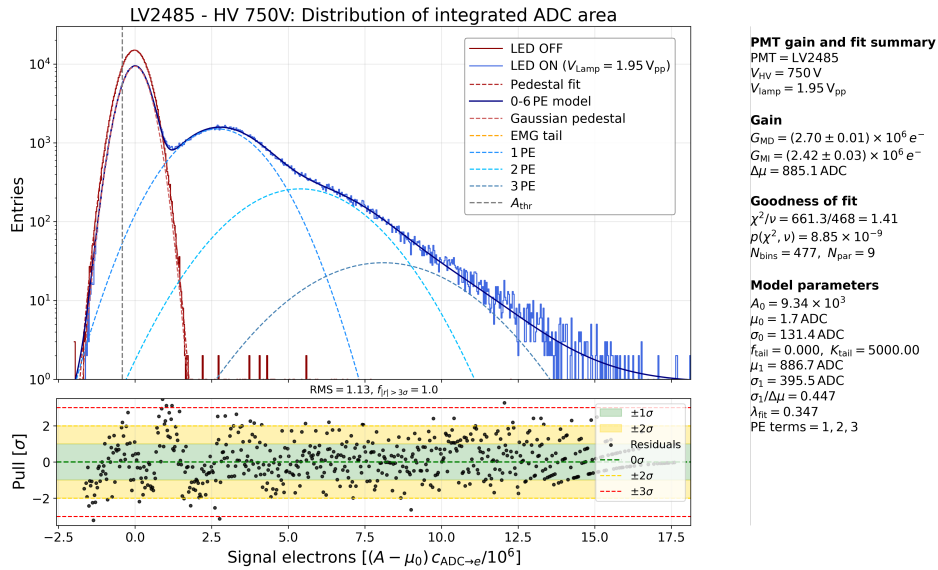


Figure 60: Integrated charge spectrum of PMT LV2485 measured at an applied high voltage of 750 V. The fitted model components and the pull residuals are shown.

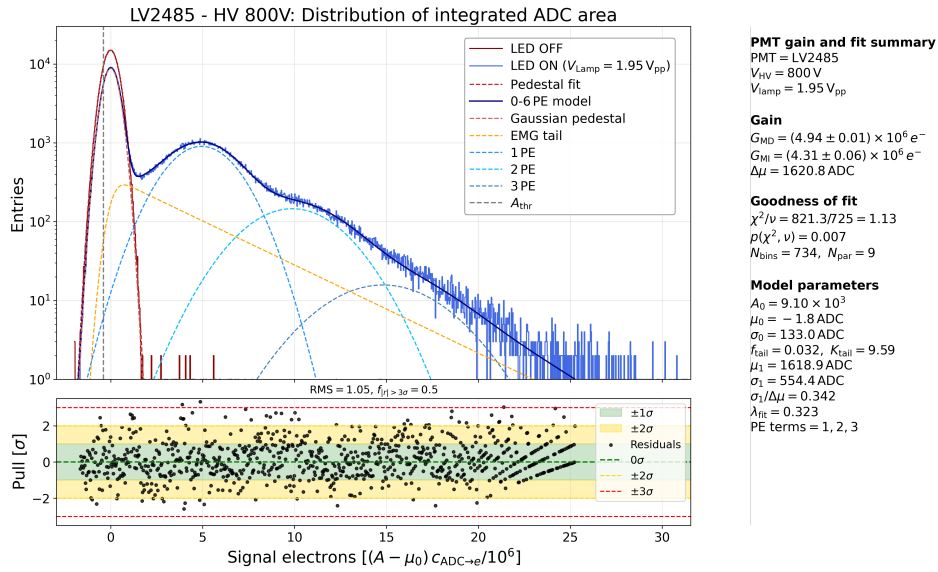


Figure 61: Integrated charge spectrum of PMT LV2485 measured at an applied high voltage of 800 V. The fitted model components and the pull residuals are shown.

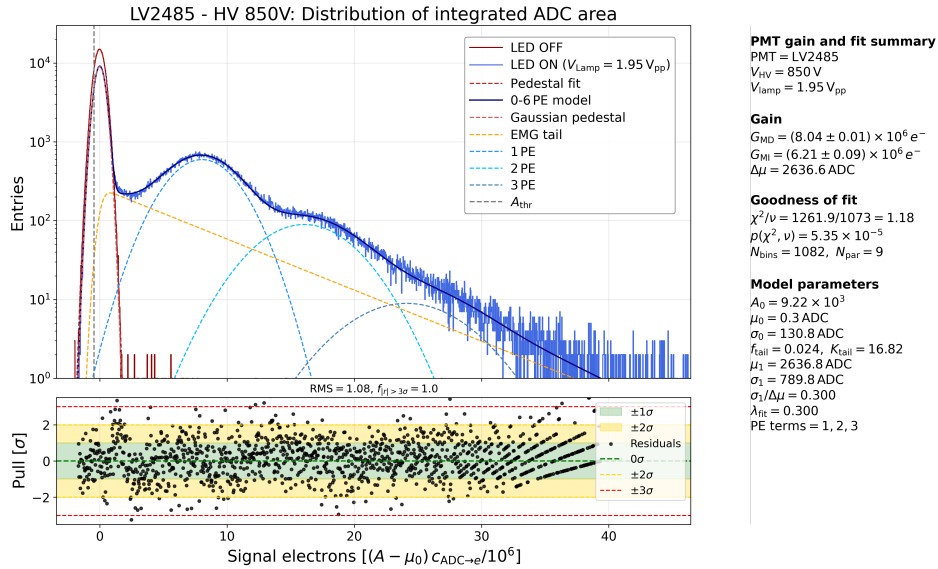


Figure 62: Integrated charge spectrum of PMT LV2485 measured at an applied high voltage of 850 V. The fitted model components and the pull residuals are shown.

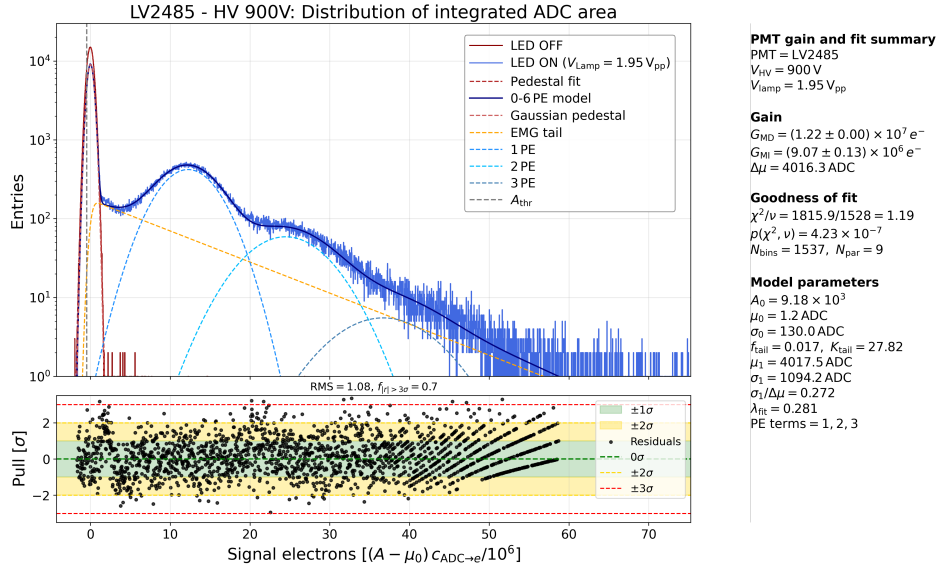


Figure 63: Integrated charge spectrum of PMT LV2485 measured at an applied high voltage of 900 V. The fitted model components and the pull residuals are shown.

B Afterpulse Plots

This section contains the afterpulse distributions obtained for the investigated PMTs. The corresponding analysis and discussion are presented in the main text.

B.1 LV2480

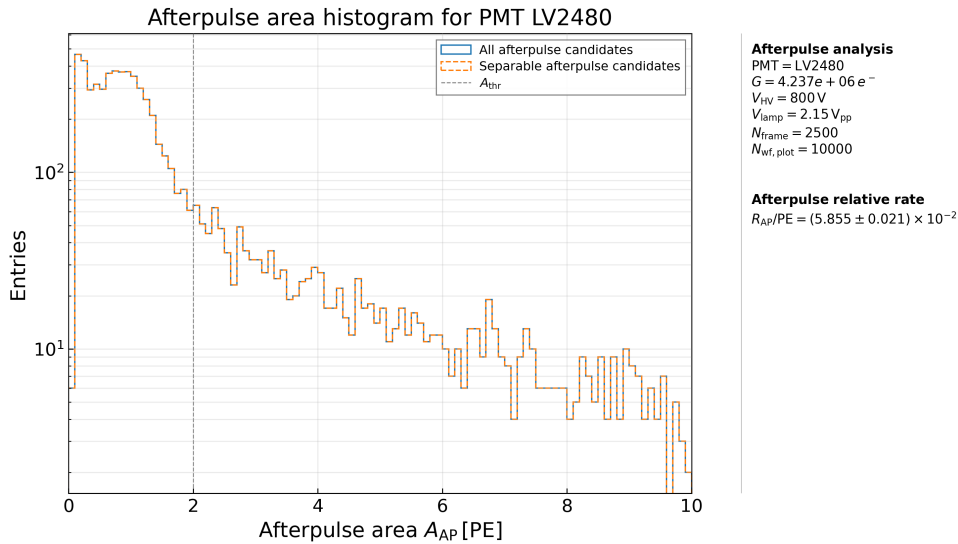


Figure 64: Distribution of the measured afterpulse areas for PMT LV2480 at an applied high voltage of 800 V.

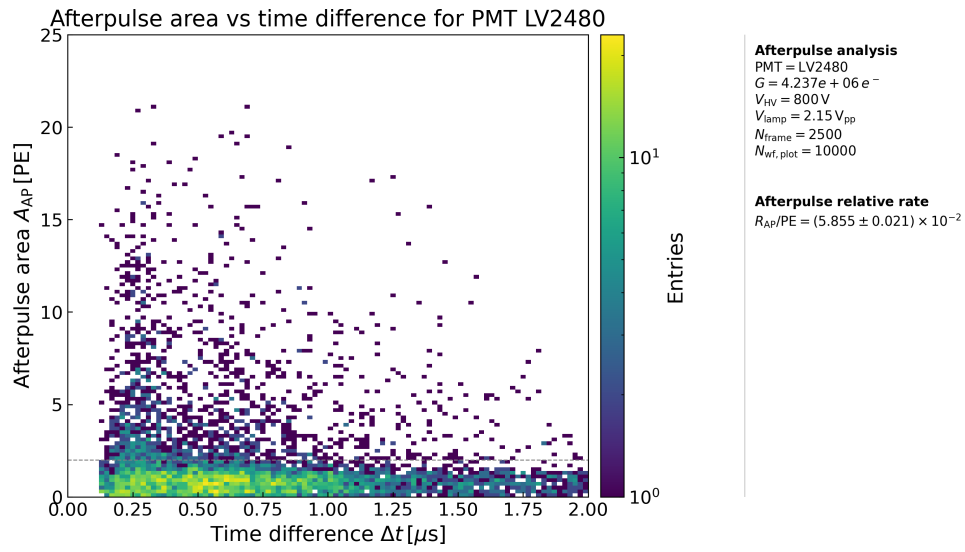


Figure 65: Correlation between afterpulse area and delay time for PMT LV2480 at an applied high voltage of 800 V.

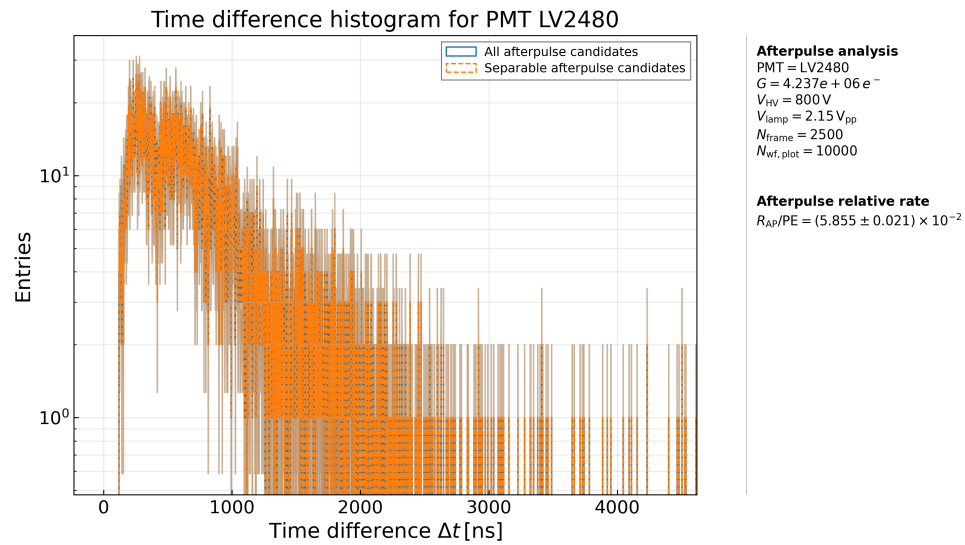


Figure 66: Distribution of the delay times between the main PMT pulse and the identified afterpulse candidates for PMT LV2480 at an applied high voltage of 800 V.

B.2 LV2481

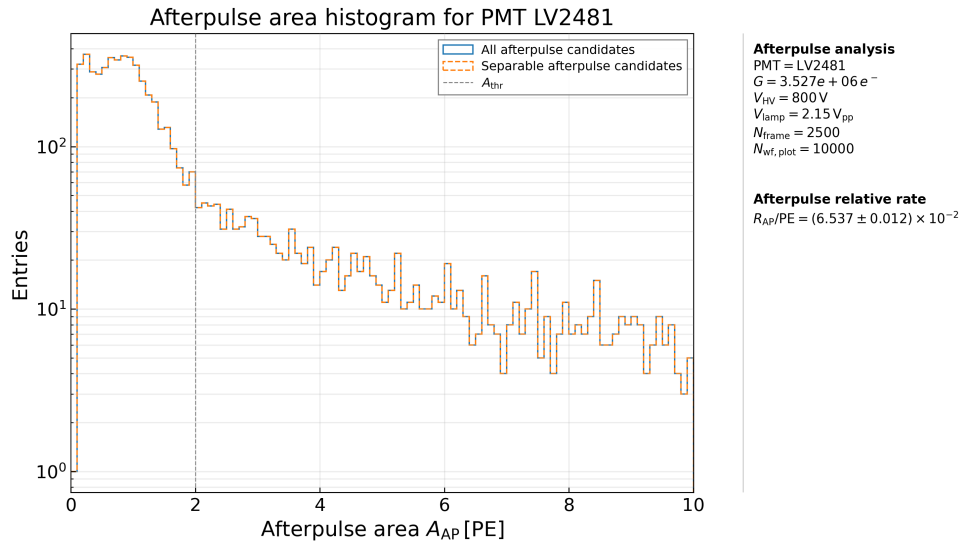


Figure 67: Distribution of the measured afterpulse areas for PMT LV2481 at an applied high voltage of 800 V.

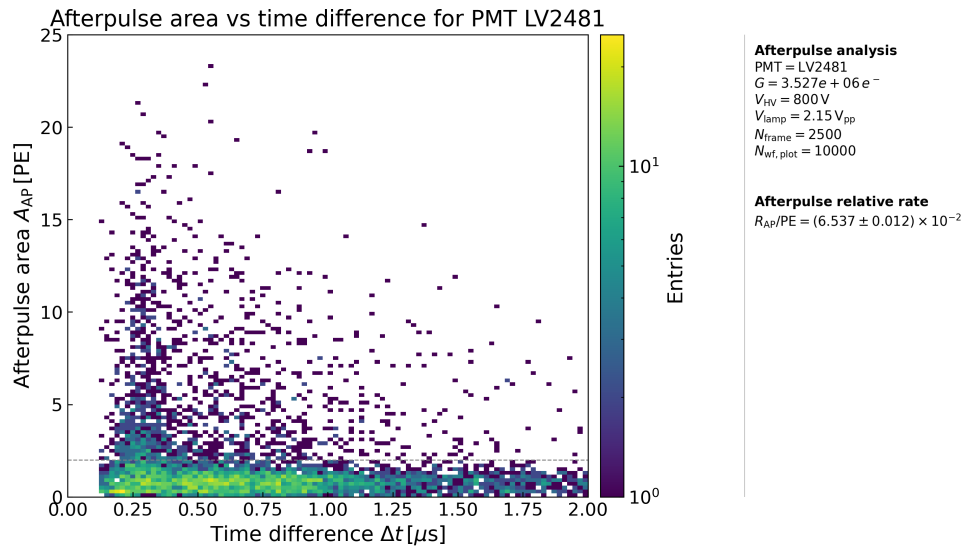


Figure 68: Correlation between afterpulse area and delay time for PMT LV2481 at an applied high voltage of 800 V.

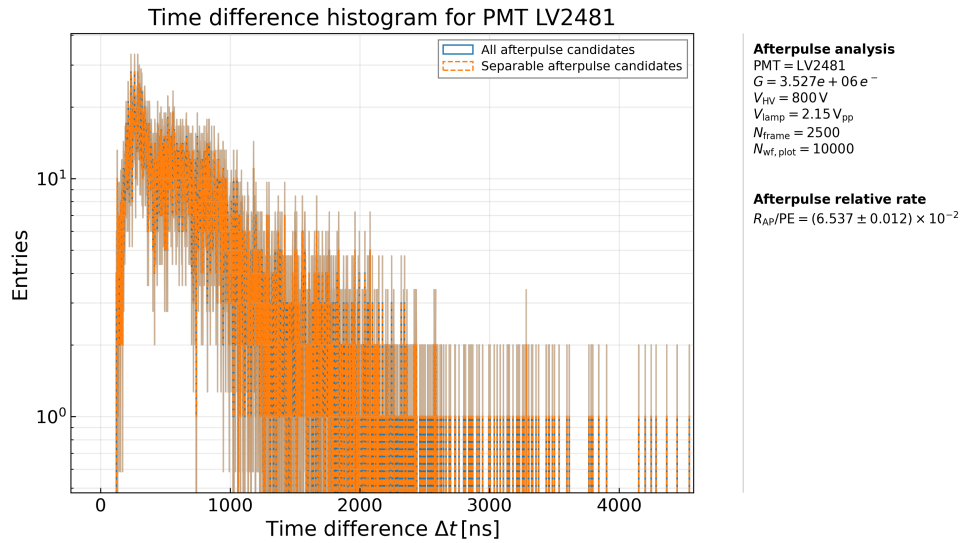


Figure 69: Distribution of the delay times between the main PMT pulse and the identified afterpulse candidates for PMT LV2481 at an applied high voltage of 800 V.

B.3 LV2483

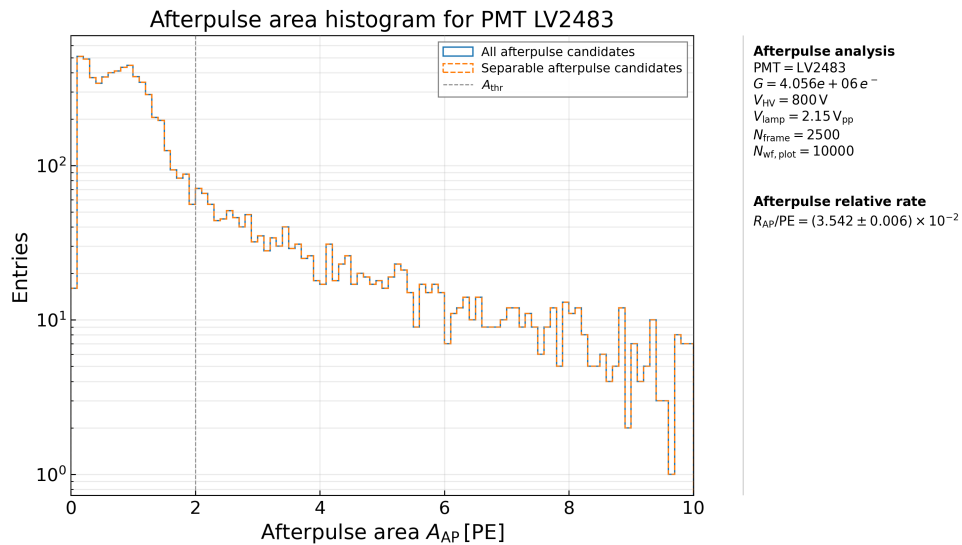


Figure 70: Distribution of the measured afterpulse areas for PMT LV2483 at an applied high voltage of 800 V.

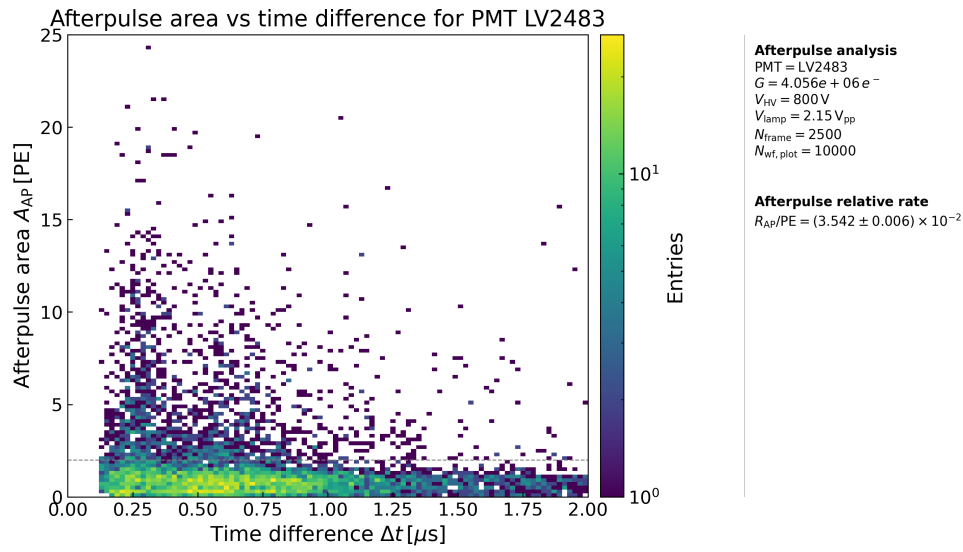


Figure 71: Correlation between afterpulse area and delay time for PMT LV2483 at an applied high voltage of 800 V.

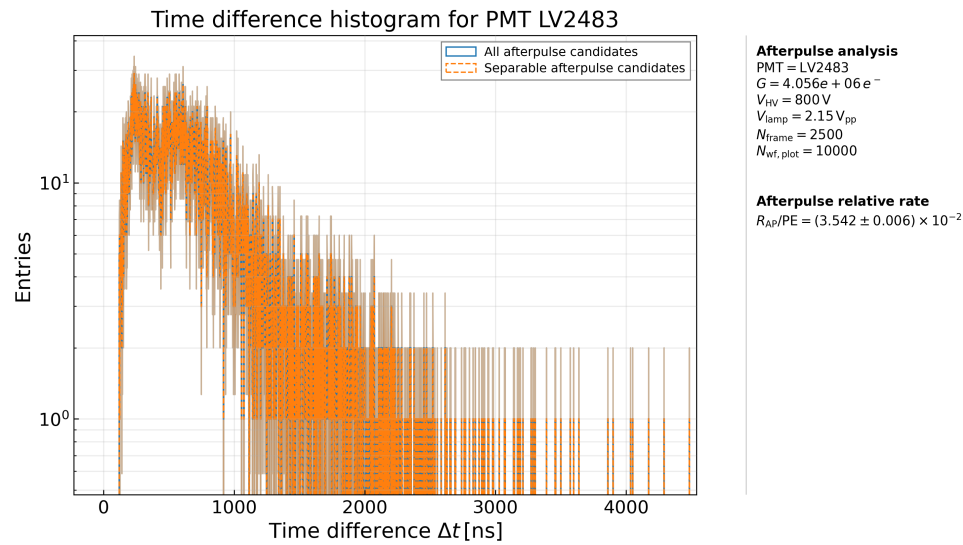


Figure 72: Distribution of the delay times between the main PMT pulse and the identified afterpulse candidates for PMT LV2483 at an applied high voltage of 800 V.

B.4 LV2485

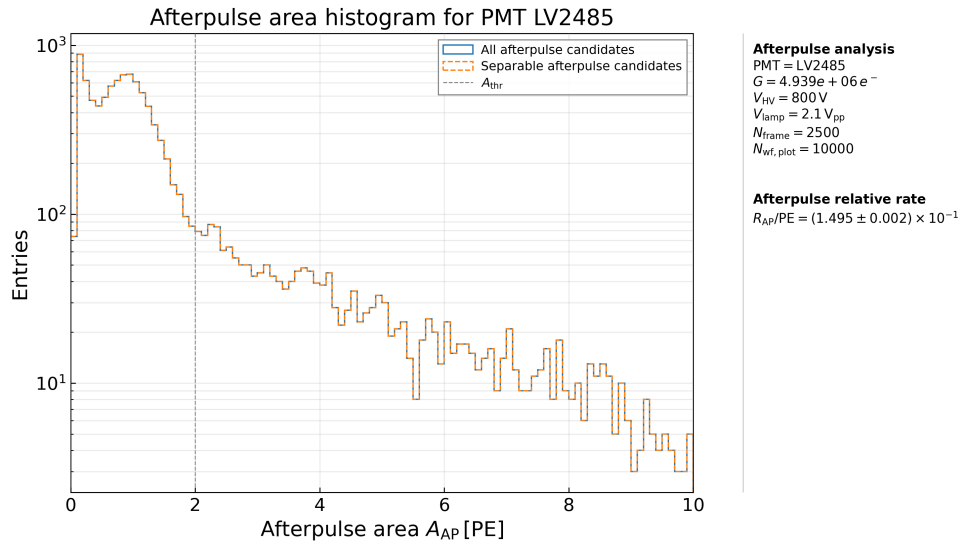


Figure 73: Distribution of the measured afterpulse areas for PMT LV2485 at an applied high voltage of 800 V.

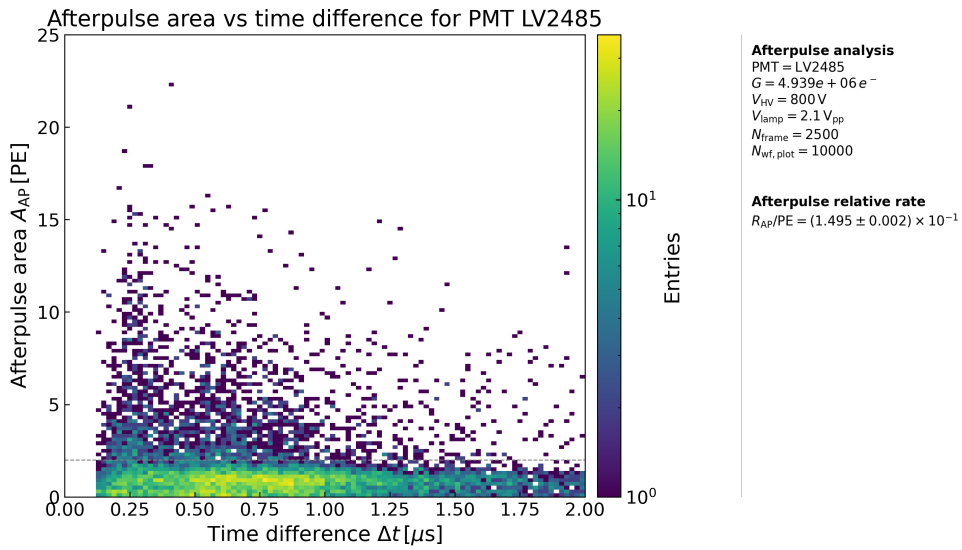


Figure 74: Correlation between afterpulse area and delay time for PMT LV2485 at an applied high voltage of 800 V.

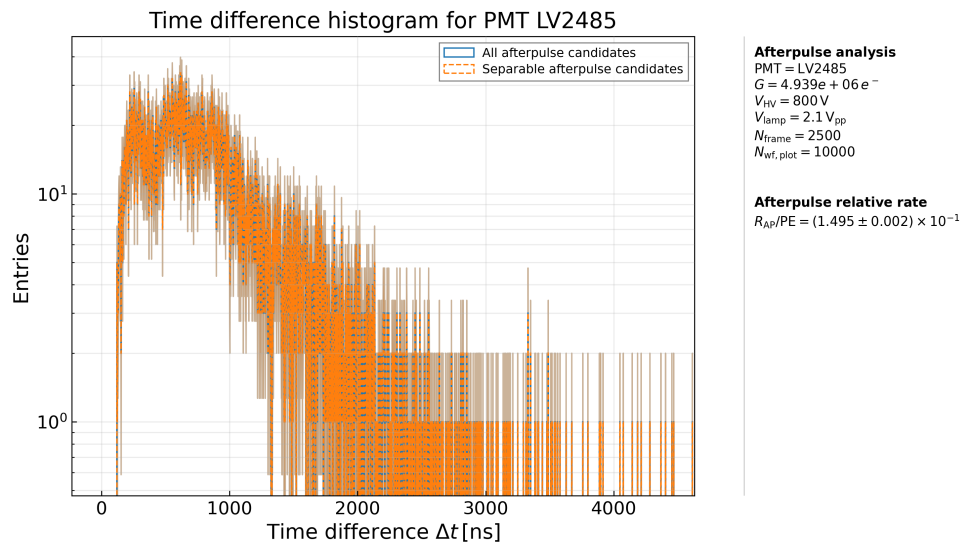


Figure 75: Distribution of the delay times between the main PMT pulse and the identified afterpulse candidates for PMT LV2485 at an applied high voltage of 800 V.

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