Design and Commissioning of a calibration facility for photomultipliers of the mDOM of the IceCube Upgrade

Master thesis in physics

by

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submitted to

Faculty for mathematics, computer science and natural sciences
of
RWTH Aachen University

written at

III. PHYSIKALISCHES INSTITUT B

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October 7th, 2019
Abstract

For the IceCube-Upgrade, a new light sensor (mDOM) is developed, which consists of multiple photomultipliers (PMTs). Each PMT has to be tested and characterized prior to assembly of the modules. An acceptance test facility was constructed to identify defective units, calibrate gain, transit time, noise rates, photon detection efficiency, and reject PMTs which emit light from the dynode system or the base. Design challenges are the large number of PMTs to be tested simultaneously, within a tight schedule, at Antarctic temperatures, and over a wide wavelength range.

The design of the acceptance test facility is presented in this thesis. All components used are presented and verified. Commissioning and first light measurements were performed and are presented. The successful implementation of the facility is described and it will go into service in the next year.
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Neutrinos are uncharged leptons in the Standard Model (SM) of particle Physics [1]. They come in three flavours as the counterparts to the charged leptons: electron, muon, and tauon (or simply tau). Even though the SM predicts neutrinos to be massless particles, the observation of neutrino oscillations requires neutrinos to have a mass [2].

Figure 1.1: In multi-messenger astronomy different particles are used to get more information about extreme regions of the universe such as active galaxy cores or supernova remnants. Taken from [3].

Since the first measurement of neutrinos in 1956 by Cowan and Reines [4], neutrino physics has become a major field in particle physics. Due to their tiny cross-section, they are usable for astronomical observations of extreme regions of the universe. Where photons would be absorbed by interstellar, intergalactic matter, and radiation fields, neutrinos can propagate through, as seen in Fig. 1.1. They are uncharged and thus not deflected by magnetic fields. In summary, they are able to reach Earth on a direct path from their formation [5].
Chapter 1 Neutrinos and the IceCube Observatory

Figure 1.2: The IceCube detector consists of 5160 DOMs which are frozen in the Antarctic ice. In the middle of the array, DeepCore is a denser instrumented volume which enables a lower energy threshold. On top is the IceTop detector array which measures air showers [6].

Cosmic rays are produced at these cosmic regions. Due to their charge, they are distracted traveling straight through space. For astronomical observations at the IceCube Observatory only high-energy neutrinos are used nowadays [1].

Neutrinos can be detected by secondary particles produced through weak interactions [1]. These particles are created in the detector medium [6]. During the propagation through the medium charged, relativistic particles induce Cherenkov light [6]. This light is formed in a cone like shape along the propagation axis of the particles. It can be detected by light sensitive devices. For the observation of high-energy neutrinos, large volume detectors are needed due to the very low rate of events per volume [1].

The IceCube detector consists of cubic-kilometre scaled ice volume at the geographic South pole in Antarctica [7]. The location was chosen due to the superior ice properties and existing logistics infrastructure at the pole. Detector construction was completed in 2011 [6]. 5160 light detectors were deployed into the ice [6]. Each of these Digital Optical Modules (DOM) holds a 10" downward facing photomultiplier tube (PMT). They are distributed over 86 strings with a 125 m lateral spacing in a hexagonal shape. The array of detectors is located at a depth between 1450 m and 2450 m as illustrated in Fig. 1.2. Eight out of the 86 strings have a much smaller spacing and form the DeepCore region. In addition, a different type of PMT with a higher quantum efficiency (HQE) was used in these DOMs (HQE DOMs). In the region of the DeepCore detector, the spacing of DOMS is denser which achieves a lower energy threshold for atmospheric neutrinos. On top of the ice, the IceTop air shower array has been deployed [7]. Since the completion, the detector has an uptime of 99% with 98.4% of the deployed DOMs.
working properly [6].

Most of the measured events are induced by atmospheric muons. These can be identified either by the IceTop detector or by a down going track of light in the detector and deposited energy [7]. Measured energies range from 10 GeV in the DeepCore volume, to up to 100 TeV [6]. In 2013, the first astrophysical neutrino was measured [8]. These extra-terrestrial neutrinos are the dominating part above these energies. So far, a few events with energies in the PeV range have been measured [8].

In addition, on 22nd September 2017, IceCube detected a 290 TeV neutrino event [9]. The directional reconstruction was consistent with the extragalactic object called blazar TXS 0506+056 [9]. Together with other optical observatories, an observation was made in different wavelengths from near infrared to 100 TeV photons [9]. This multi messenger observation might lead to a much better understanding of similar objects in the future [9].

Besides the ongoing search for possible multi messenger objects, the search for neutrinos at lower and higher energies outside of the existing limits of IceCube is interesting for future research efforts. In the following chapter, possible goals, requirements, and solutions are discussed for the IceCube Upgrade.
This chapter presents an overview of the goals of the IceCube Upgrade and resulting requirements for new sensors. The multi-PMT Digital Optical Module (mDOM) will be discussed as a new sensor module. Furthermore, photomultiplier tubes (PMTs) and the proposed options for the mDOM are presented.

2.1 Upgrade scientific goals and requirements

With the IceCube detector now running for nearly 10 years, there are possible improvements which can extend the sensitivity and lead to a better understanding of the glacial ice \([10]\). As the first step, the IceCube Upgrade will lower the energy threshold to a few GeV in the DeepCore region. This will be achieved by the installation of seven new strings with a denser spacing of detectors. The Upgrade will also improve the measurement sensitivity of neutrino oscillations and enable the detector to take measurements of tau neutrinos appearance with a high precision \([10]\). The planned deployment is during the 2022/23 Antarctic Summer season \([10]\).

For the whole Upgrade, roughly 700 newly developed optical sensor modules will be deployed into the ice. They will be inserted at the DeepCore region as shown in Fig 2.1 and Fig. 2.3. The array of photon sensors will be placed at depths between 2150 m and 2425 m and will have a lateral spacing of 20 m and a vertical spacing of 3 m. The positioning will differ from string to string as shown in the figure.

The used optical devices are the multi-PMT Digital Optical Module (mDOM), the Dual optical sensors in an Ellipsoid Glass for Gen2 (D-Egg), and the PINGU Digital Optical Module (pDOM) \([10]\). As illustrated in Fig. 2.2, all of these devices are displayed with their positioning on the string. The pDOM, which is the second generation of the deployed DOMs of IceCube, holds a downward facing 10" PMT. They are located above and below the DeepCore depth. The omnidirectional mDOM houses 24 3" PMTs. In section 2.2, this device will be discussed in detail. Together with the D-Egg, they are deployed at the DeepCore depths. This D-Egg holds two along the vertical axis facing 8" PMTs. In addition to these sensors, different calibration and ice measurement devices will be installed in the array. The Precision Optical Calibration Module (POCAM), for example, is a calibration light source for the new array \([12]\). It emits isotropic, nanosecond light pulses of adjustable intensity and duration.
Figure 2.1: The red dots show the position of the seven Upgrade strings together with the existing ones. The sensors have a vertical spacing of 3 m which is denser than on all other strings [10]. Taken from [10].

Figure 2.2: Schematic sketch of the three new optical sensors and their orientation on the strings. The pDOM is the next generation with updated hardware from the DOM consisting of one downward facing 10" PMT and is placed above and below the DeepCore depth [10]. The mDOM consists out of 24 3" PMTs and can detect light from all directions [10]. In conjunction with the D-Egg which holds 2 up- and downward facing 8" PMTs, they are installed at the DeepCore depth [10]. Taken from [11].
2.1 Upgrade scientific goals and requirements

![Figure 2.3: The positioning of the sensors is shown. The Upgrade will consist out of different newly developed sensors, displayed in different colors, while IceCube itself and DeepCore have only DOMs. Taken from [10].](image)

2.1.1 Future IceCube extensions

In a further step, the existing IceCube detector volume of roughly 1 km$^3$ should be extended to 10 km$^3$ [8]. This extension will improve the angular resolution of the detector and extend the energy range beyond PeV-scale. A higher neutrino measurement rate at high energies will gain the potential of new discoveries such as the measurement of GZK neutrinos [10]. These are neutrinos produced by the interaction of extragalactic cosmic rays with the microwave background [13].

About 120 new strings should be deployed into the ice for the so called Gen2 detector [8]. The strings should have a lateral spacing of 240 m to 300 m [8]. The light sensitive hardware is an updated version of the DOM. Based on the experience of designing and deployment of the IceCube project, most improvements are focused on modernizations, efficiency, and cost savings [8].

The future of IceCube Gen-2 is not yet finally decided. In the first step, the smaller part of IceCube-Gen2 will be realized with the Upgrade.
2.2 The multiple-PMT Digital Optical Module

Various new light detectors are being developed for the IceCube Upgrade [7]. This chapter will present the light detection hardware of the IceCube detector, the DOM. Further, the multi-PMT Digital Optical Module (mDOM) will be discussed in detail.

2.2.1 The Digital Optical Module

The light detection device in the IceCube detector is the Digital Optical Module (DOM) [7]. These spherical devices, shown in Fig. 2.4, incorporate a 10” diameter R7081-02 photomultiplier tube (PMT) made by Hamamatsu Photonics. The PMT is encapsulated by a Mu-metal grid to shield magnetic fields [7]. The PMT is optically coupled to the glass vessel with RTV\(^1\) gel [7]. All necessary electronics are located inside of the 0.5” thick glass sphere. In addition to the PMT high voltage generator and divider, there is the mainboard which hosts analogue and digital processing electronics [7]. The vessel also contains an LED flasher board for calibrations of the DOM’s position and measuring of the ice properties [7].

The optical transmission of the glass vessel is 93% at 400 nm and 50% at 340 nm [6]. Over the years of operation, the design has proven itself reliable [6]. Only about 0.6% of all DOMs have failed operation over the years [6]. This was achieved by verifying the functionality of every DOM after assembling [14]. The final acceptance testing (FAT) was performed near the production site in a so called dark freezer laboratory (DFL) [14]. Processes in the DFL are standardized and were conducted in three different production sites (Madison (US), Zeuthen (Germany), Stockholm (Sweden)). Each testing cycle took roughly 3 weeks [14]. All measurements were done at different temperatures. These varied from 20°C down to -55°C [14]. Furthermore, measurements were performed at various temperatures to verify different aspects of the DOMs, such as the basic functionality, PMT calibrations, dark noise, optical sensitivity, time resolution, and DOM pulse linearity [14]. An LED pulser, a 405 nm diode laser, and a monochromator-tuned quartz tungsten halogen lamp were used as light sources. The light was distributed into the DFL via optical fibers. There, the light was fed through a diffuser to homogeneously illuminate the DOM. This whole procedure ensures that each device was properly calibrated and failing or poorly-operating devices could be sorted out [14].

\(^1\)Room-Temperature-Vulcanizing
2.2.2 Requirements to the DOM

The operation of light detectors in Antarctic ice has special challenges. That leads to the following requirements which were formed for the design of the DOM. For future applications, this is considered.

- The diameter of the sphere can not exceed 13” to 14” due to the chosen radius of the drill in the ice. Hot water is used to drill the holes. The technical process is well understood and it is not economic to scale up in diameter [1].

- While the water in the borehole refreezes, the pressure increases significantly. This pressure to the vessels can reach up to 690 bar. Due to this, the vessels and connectors must withstand pressures of up to 700 bar [1].

- The whole device must be fully operational at temperatures below -30 °C and must withstand temperatures as low as -70 °C while in storage [1].

- The wavelength spectrum of Cherenkov light results in an optical module sensitivity maximum near 400 nm [15]. Incidentally at this wavelength, the transparency losses are balanced with the scattering lengths in the ice. Therefore, the glass vessel should be also transparent to these photons to be able to detect them [1].

2.2.3 The mDOM concept

In contrast to the single PMT approach, other large-volume neutrino detectors follow a different approach. The KM3NeT project uses a multi-PMT light detector [16]. For this project, three blocks of 115 strings with 18 light detectors each, will be deployed into the Mediterranean Sea [16]. These detectors are 17” in diameter and house 31 3” PMTs each [16]. As a "spin-off" of the development of these devices, the mDOM is considered as a smaller companion for the IceCube extension [1]. Different to the sea water for KM3NeT, in IceCube, glacial conditions have to be considered for the design.

The design of the mDOM took place in parallel to the development of the KM3NeT detectors. It was considered to build a 14” glass vessel housing 24 3” PMTs. In comparison to the old single PMT layout, there are several advantages to the multi-PMT layout [17]:

- The sensitive area of ten 3” PMTs equals the area of a 10” PMT. This indicates an increase in sensitive area of roughly factor two. As the measurement of photons is essential for a neutrino detector, the information gained per event is larger than with the conventional single PMT design [1].

- The dynamic range of the whole detector benefits from splitting the cathode due to the probability of multiple photons coming from one direction hitting different PMTs. The collective range is extended by the factor of the numbers of PMTs facing the same direction while assuming comparable dynamic ranges for small and large PMTs [1].

- By facing the PMTs across the total solid angle, the coverage approaches $4\pi$. The knowledge of the incoming photon direction is additional information which can lead to a better reconstruction of events [1].
Chapter 2 The IceCube Upgrade

Figure 2.5: The mechanical layout of the multi-PMT Digital Optical Module (mDOM) is shown. The pressure vessel is 411 mm in height and has a diameter of 356 mm [1]. The omnidirectional mDOM houses 24 3" PMTs [1]. Each of them has its own active base soldered at the back [1]. The mainboard with analogue and digital processing electronics is located in the middle of the device [1]. Taken from [1] and [11].

- The possibility of using local coincidences to suppress noise of PMTs obtains a much better background identification and leads to an easier identification of low energy neutrino events [1].

2.2.4 Mechanical design

The mDOM is shown in Fig. 2.5. The used pressure vessel is made out of borosilicate glass, 411 mm in height, and has a diameter of 356 mm [1]. Based on simulations by the manufacturer, Nautilus GmbH, the vessel can withstand pressures of up to 700 bar [17]. This was tested and confirmed [18]. Each PMT has its own active base which generates the high voltage required to run the PMT on board [17]. The mainboard with analogue and digital processing electronics is located in the middle of the vessel. For optical coupling and mechanical stability, the PMTs are glued into the glass vessel using QGel 900 [17]. This gel, produced by Quantum Sillicones, was also used in the DOM and has proven itself to be a reliable gel, especially at low temperatures [17]. To increase the effective area of the PMTs, light reflectors are mounted around the PMTs. This increases the module sensitivity roughly by 20% [17]. The reflector’s shape is optimized to yield a maximum sensitivity for vertical photons [17]. By this configuration, the opening angle of each PMT is 51° with respect to the symmetry axis of the PMT [17].
2.3 PMT selection

Before taking a closer look at the requirements for the operation of PMTs in the Antarctic ice, the general structure and functional principle of a photomultiplier tube is discussed in the following.

2.3.1 Photomultiplier tubes

PMTs are very sensitive light detectors [19]. Their sensitivity ranges from single photon measurements up to several thousand photons per pulse [1]. Since their first introduction back in the 1930s, they have become a reliable light detection device in physics [1]. The field of applications ranges from scintillation counting over gamma ray astronomy to neutrino detection [1].

The basic PMT layout is shown in Fig 2.7. There are several electrodes forming a dynode system located inside an evacuated glass tube [19]. On the inner side of the entrance window, the photocathode is located [19]. When a photon hits the photocathode, an electron can be emitted by chance [19]. Moreover, the probability, called quantum efficiency (QE), is in the order of 15% to 25%, depending on the material of the photocathode [19]. For special PMTs, like high quantum efficiency PMTs used in the DeepCore region, the QE can reach up to 30% at 400 nm [20]. The photoelectron is accelerated by an applied high voltage to the first dynode where it is multiplied [19]. Over a following chain of dynodes the electron gets multiplied by a factor of $10^5$ to $10^7$ [19]. This factor is called the gain of the PMT and is highly dependent on the applied high voltage to the PMT [19].

An electrical signal is read out at the anode [19]. These components, together with the voltage divider are soldered on the base, which is attached to the back of the PMT’s flying leads [19]. This is shown in Fig. 2.6.

Furthermore, two different base designs are considered for the operation of PMTs. In the passive base, just passive components are used [1]. The high voltage for the PMT must be provided by an external power supply. In contrast to this, the active base provides high voltage by onboard active components. They are able to ramp up an input voltage of 5 V, provided via a serial connection, to the high voltage, necessary for the operation of a PMT [1]. For the mDOM the active base layout is chosen [1].
Chapter 2 The IceCube Upgrade

Figure 2.7: A schematic view of a photomultiplier tube (PMT) is shown. All components are sealed in an evacuated glass tube [19]. An incoming photon hits the photocathode and produces a photoelectron by chance [19]. This probability is called quantum efficiency (QE) and can reach up to 30% for specially coated photocathodes at a wavelength of 400 nm [20]. By applying a high voltage, the photoelectron gets accelerated to the first dynode [19]. There, the electron gets multiplied. These secondary electrons get multiplied further until reaching the anode. Subsequently, a signal can be read out. Picture taken from [21].

2.3.2 PMT properties

The variety of PMTs is huge. PMTs are build in different sizes, shapes, or pin layouts. They can be particularly designed for special applications. Alongside of the mechanical and electrical properties, there are a lot of different physical characteristics. In the following, features of PMTs studied in this thesis will be discussed.

Average waveform

In Fig. 2.8 on the left, the average of 4262 waveforms is displayed. The waveform reaches nearly 3 mV and has a duration of 20 ns and less. The steep rise is the measured electron cascade between the last dynode and anode. After the voltage has dropped, the voltage rises again to the applied value. Each waveform is corrected by subtracting the baseline. This baseline is the noise generated while digitizing the analog signal. The waveform is characterized by its rise and fall time, the maximal pulse height, and the pulse length [22]. As the name suggests, the maximal pulse height is the highest value of the pulse. The rise time is defined as the time during which the pulse rises from 10% to 90% of its maximum [22]. Equally, the fall time is the time difference between the pulse falling from 90% to 10% of its maxima [22]. The pulse length is the time difference measured between 50% on the rising edge and 50% on the falling edge [22].
2.3 PMT selection

(a) Average waveform

(b) SPE spectrum

Figure 2.8: On the left, an average waveform of a HZC Photonics XP72B20 is shown. For this, 4262 waveforms were averaged. On the right, a single photoelectron spectrum is shown. The left and highest maximum is called “pedestal” and contains all waveforms without any pulse. The wider maximum on the right is called “SPE peak” and contains all waveforms with single photoelectron (SPE). In-between these two is the “valley” [23].

Single photoelectron spectrum

A single photoelectron spectrum (SPE) is shown on the right in Fig. 2.8. To measure this distribution, the PMT is illuminated with a dim light source to achieve an occupancy of around 5% to 10% [23]. This means that one photoelectron is measured in every 10th to 20th waveform. For the calculation of the measured charge $Q$ of one PMT pulse, the voltage $U(t)$ has to be integrated over a time window from $t_{\text{begin}}$ to $t_{\text{end}}$. $U(t)$ is divided by the impedance $R$ of the output signal line [22]. The equation for this charge is then given by:

$$Q = \int_{t_{\text{begin}}}^{t_{\text{end}}} \frac{U(t)}{R} \, dt$$

(2.1)

The resulting histogram has a Gaussian peak at around $Q = 0$ pC called "pedestal", which contains waveforms without a pulse [23]. Depending on the applied voltage, at higher charges there is a wider, smaller Gaussian peak called "SPE peak" [23]. The SPE of the PMT build this peak. In-between these two, there is the "valley" [23]. Taking the ratio of the valley’s height and the peak’s height, the peak-to-valley ratio gives an indication of how good digitization noise can be separated from a SPE signal [23]. The standard deviation of the Gaussian fit divided by the SPE peak’s position is called SPE resolution. It has the unit photoelectron (PE) which equals the charge of the SPE peak’s mean value.

Gain over high voltage

The amplification of a PMT is quantified by the gain. This is the number of detected electrons on the anode per number of freed electrons at the first dynode [24]. The gain of a PMT depends on the applied high voltage [19]. The higher the voltage, the higher the gain [19]. This dependency is characterized by an exponential function. There, the gain is defined as the fraction of the SPE peak’s charge over the elementary charge. By repeating this for different
Chapter 2 The IceCube Upgrade

Figure 2.9: On the left, a gain over high voltage plot is shown. At a voltage of 1142 V, the PMT reaches the nominal gain of $5 \cdot 10^5$. On the right, a transit time histogram is shown. The main peak is estimated by a Gaussian. The width of the Gaussian is defined as the transit time spread (TTS). Before the main peak, there are random and pre-pulses. After the main peak, there are delayed pulses. Right taken from [23].

Transit time spread

The characterisation of the timing behavior of a PMT signal can be done by making a transit time histogram, as shown on the right in Fig. 2.9. A pulsed light source is used to illuminate the PMT [23]. Afterwards, the time difference between the trigger of the light source and the arrival time of the pulse is measured and added to a histogram [23]. The highest peak of the histogram indicates the time of the main pulses [23]. The transit time spread (TTS) is measured by the spread of the Gaussian [23]. The pulses before the main peak are random or pre-pulses where the photon does not produce a photoelectron at the photocathode but at the first dynode [23]. Pulses right after the main peak are called delayed pulses. The main reason for their appearance is backscattering of the photoelectron at the first dynode. The TTS is in order of a few ns. By counting all delayed pulses and dividing by the number of pulses in the main peak, the late pulse probability is calculated [24]. Additionally, there is a probability for afterpulses [19]. These pulses are induced by ionized particles of residual gas atoms in the vacuum tube [19]. Due to their positive charge, they drift towards the photocathode and can induce an electron there, which is like a photoelectron [19].

Dark noise

One important property of the PMT background is the dark noise rate. This issue is especially important for PMTs used in the IceCube detector, where very dim light events are measured [7]. The dark noise rate is defined by the number of PMT pulses in a certain amount of time where the PMT is not illuminated [24]. In Fig. 2.10 on the right, a histogram of the time differences
2.3 PMT selection

(a) Dark noise over time

(b) Dark noise over temperature

Figure 2.10: The plot on the left shows a histogram with time differences between a pulse and delayed noise pulses. Most of the noise pulses happen within the first few milliseconds after the pulse and are correlated. If the time difference of the second pulse is higher than 6 ms, they are called noises uncorrelated. On the right plot, the dark noise rate at different temperatures is shown. By going to lower temperatures, the thermal noise decreases to a nearly constant level below -20°C. Taken from [6] and [24].

between two consecutive noise pulses is shown. Most of the noise pulses appear in a short time window of a few milliseconds after the first PMT pulse. Further, the correlated noise is caused by natural radioactive decays, producing two or more photons. The noise pulses are random coincidences after a time difference of $\Delta t > 6$ ms and are called uncorrelated noise. The temperature dependence of the dark noise is shown on the left. By decreasing the temperature, the noise rate decreases to a nearly constant level, which is reached at -20°C. At this point, the thermal dark noise has reached its minimum [24]. An artificial dead time can be added to the measurement, as the new pulse would only trigger a new readout while the acquisition is already running. This reduces the dark noise rate, especially at low temperatures.

2.3.3 PMT requirements

Over the years of operation of the IceCube detector, the following PMT requirements have proven to be important for the reliable operation of the 10" PMTs. Considering these requirements for the IceCube Upgrade can support an undisturbed operation.

- The PMTs should have a nominal gain of $10^7$. This leads to a single photon pulse height of around 8 mV. This is well discriminable from electronic noise [7].

- The photocathode must have a high QE around 400 nm. In this wavelength region, the Cherenkov light is most prominent after propagation through the ice [15].

- The dark noise of the PMT must be lower than 300 Hz at low temperatures to reduce the background of the whole detector. To achieve this, custom low radioactive glass is used for the PMT [7].
• For the aimed power consumption limit of 5 W, the PMTs must have a small leaking current [1].

In addition, there are the following tender specifications for PMTs for the Upgrade. These are the specifications for all smaller PMTs for the mDOM:

• The PMT must be able to operate at temperatures between -45 °C and +30 °C [25].
• The temperature range for storage of the PMTs must be from -60 °C to +50 °C [25].
• The maximal diameter of the PMT must not exceed 111 mm and the total length must not exceed 95 mm [25].
• The PMT must reach a gain of $5 \cdot 10^6$ at 950 V to 1350 V [25].
• The photocathode must have a QE of 7% or higher at 325 nm, 25% or higher at 380 nm, and 15% or higher at 500 nm [25].
• The average amplitude of a one PE pulse must be higher than 6 mV [25].
• The 10% to 90% rise time must be in the range of 1 ns to 5 ns [25].
• The SPE resolution must be less than 0.7 PE as defined by the standard deviation of Gaussian fit of the SPE peak [25].
• The peak-to-valley ration must be larger than 2 [25].
• The dark noise rate must not exceed 150 Hz at a temperature of -20 °C, as measured with a deadtime of 100 ns [25].

These specifications must be warranted by the manufacturer. In addition, it is necessary to test each PMT prior the assembly into the mDOM. This is discussed in chapter 3. There are

![Image](a) R12199-02 MOD HA (b) XP82B20D

Figure 2.11: On the left, the 3” R12199-02 MOD HA manufactured by Hamamatsu Photonics is shown. On the right, the 3.5” XP82B20D manufactured by HZC Photonics is shown. Both PMTs are shortlisted for the operation in the mDOM.
two various closer inspections of usable PMTs, which fulfill all specifications and are discussed in the detailed selection [23]. One is the R12199-02 MOD HA manufactured by Hamamatsu Photonics and the other is the XP82B20D manufactured by HZC Photonics [23]. These will be discussed further in the following sections.

2.3.4 Hamamatsu R12199-02 MOD HA

The current baseline PMT for the mDOM is the 3” PMT R12199-02 MOD HA manufactured by Hamamatsu Photonics, shown in Fig. 2.11a [23]. The PMT has 10 dynode stages, is made out of borosilicate glass, has a bi-alkali photocathode, and is 93 mm long. The first tested iteration of the R12199-02 performed well overall, except of the noise behaviour at low temperatures [1]. 18% of the tested PMTs had a dark noise rate higher than 2 kHz [1]. To improve on this, the PMT got a special "HA coating" which is shown as a schema in Fig. 2.12. This cover is made out of a conductive layer which is on the potential of the photocathode [19]. This reduces the impact of surrounding electrical potentials [19]. The whole layer is covered with an isolating layer for safety [19]. Simulations and measurements show that the "HA coating" reduces the dark noise of the PMT [22].

2.3.5 HZC Photonics XP82B20D

The alternative PMT for the use in the mDOM is the XP82B20D.

The PMT manufactured by HZC Photonics is a possible alternative to the R12199-02 and is shown in Fig. 2.11b [1]. It has a diameter of 3.5”, which is an increase of photosensitive area of 20% [23]. The PMT also has 10 dynode stages, is made out of borosilicate low-K glass, and has a bi-alkali photocathode [23]. Three PMTs were tested in detail and achieved good results [24].

Both, the R12199-02 and the XP82B20D are in good agreement with the specifications as provided by the manufacturers [23]. They are both well suited for the operation at low temperatures and are a reliable option for the use in future IceCube optical modules [23].

Figure 2.12: Around the glass vessel of the PMT, there is a conductive coating which is on the potential of the photocathode [19]. This reduces the impact of surrounding electrical potentials on the noise behaviour [19]. The conductive layer is encased in an isolating protection cover[19]. Taken from [19].
Before each PMT is assembled into the mDOM, it has to be tested if all specifications are fulfilled. Thus, a standardized acceptance test facility is needed to achieve comparable measurements of all PMTs. The test facility has to be able to perform different measurements. There will be around 400 mDOMs deployed in the IceCube Upgrade \([1]\). Each mDOM holds 24 PMTs, the total number of PMTs reaches roughly 10,000, which have all to be tested prior to the assembly. In addition to this large amount of PMTs, they all have to be sorted into similar nominal voltage categories to avoid large voltage differences in the mDOM \([22]\).

This chapter will take a closer look on the specific requirements of the test facility, introduce the measurement strategy, and give an overview of the systems used in the acceptance test facility.

### 3.1 Requirements to the PMT acceptance test facility

As discussed in the previous section, many requirements to the PMTs have to be considered for acceptance testing. Every PMT has to be tested before assembly into the mDOM as it has to be ensured that all PMTs fulfill the tender specifications. Due to the huge amount of PMTs, it is advisable to test as many PMTs as possible in parallel. To achieve a comparable result, it is necessary to have a standardized setup, if there is more than one test site, and to have a consistent setup itself. This means that, no matter on which position a PMT is tested, the results have to be in agreement.

In the acceptance test the PMTs and electronics should be configured as in the mDOM. This implies testing of fully assembled PMTs only with active bases and using the digitization of the mDOM mainboard. Until the end of 2019, a prototype is not available. Therefore, an alternative has to be considered for the commissioning of the test facility \([26]\). The considered solution uses a flash analog-to-digital converter (FADC). This device will be discussed further in section 4.5.1.

Not all tender specifications for the mDOM PMTs can be tested in standard conditions. Especially the temperature dependent measurements have to be performed in a temperature controlled environment. The lowest temperature needed for the tender specifications of a PMT is \(-45\,^\circ\mathrm{C}\). The test facility should be able to reach down to this temperature.

While the temperature inside the facility ranges from \(+20\,^\circ\mathrm{C}\) down to \(-45\,^\circ\mathrm{C}\), the stability of light sources has to be ensured. To achieve this, the only reasonable solution is to operate
the light sources outside of the cooled environment. Outside, the light sources have stable temperature conditions. The light is then fed into the facility using an optical fiber. In addition, the testing room must be dark to be able to perform all light sensitive measurements.

The test facility must be able to perform the following measurements to verify the tender specifications. These are:

- Verification of tender specifications
- Monitoring of PMT production quality
- Pre-calibration of all PMTs
- Sorting of PMTs into different nominal voltage ranges
- Identification of light emitting PMTs

It should additionally be able to perform long term stability monitoring of all taken parameters. The main focus of the acceptance test facility is to test the tender specifications of the PMTs. As stated by the tender specifications, all PMTs have to be calibrated at the outgoing goods control of the manufacturer. This has to be cross-checked and poorly working or faulty PMTs must be sorted out. Measuring all tender specifications individually for each PMT should require a considerable amount of time and equipment. To accommodate all measurements and tests, around 100 PMTs will be tested in parallel. Detailed information on the setup are given in chapter 4. The planned measuring strategy is discussed in the next section.

Over the time of operation of the test facility, all measured variables are monitored. This ensures that all PMTs have comparable properties. Moreover, a change in production quality can be detected and the manufacturer can be notified.

After the testing of PMTs, every PMT is sorted into a group of similarly performing PMTs. Another important task of the acceptance test facility is the search and identification of light emitting PMTs. For the operation of 24 PMTs in a small space, it is essential that no PMT or electronic component produces any light accidentally. It is possible that light is produced inside of the dynode system of a PMT or at the active base over corona discharges by chance. Furthermore, additional measurements and tests should be able to be performed with the existing setup without any huge modifications.

To perform all measurements and ensure a stable quality of PMTs, a measuring strategy was created which is explained in the next section.

### 3.2 Measurement strategy

The combination of all requirements of the acceptance test facility is not trivial. The chosen approach is based on a repeated measurement chain. A detailed overview is provided in section 3.2.2. In the following, the detailed concept of the setup is discussed.

#### 3.2.1 Concept of the setup

The optimization of the setup focuses on a fast testing procedure for many PMTs. Therefore, 100 PMTs are tested in parallel. The planned test cycle has a duration of two days and resolves into 3 runs per week, which results in 300 tested PMTs per week and test site. Thus, all PMTs
can be tested over a few months of operation. One of the main requirements is testing fully assembled PMTs as they will be deployed in the mDOMs. The container used is a 20 ft ISO shipping container. This container is equipped with an internal cooling unit which can provide temperatures down to -30°C. This enables testing at polar temperatures.

At least five PMTs are used as reference to monitor the whole test procedure. They can be changed in position for each run.

### 3.2.2 Two-day cycle

The proposed measuring cycle lasts two days. This section gives a detailed view of the proposed measuring cycle. In Fig. 3.1 the cycle is shown as a schematic illustration. All measurements are performed inside of the ISO shipping container.

1. **Loading:** All PMTs are loaded into the test facility on the afternoon of the first day. To reduce the loading time, the mechanical setup is optimized for fast mounting inside the container. Details are explained in section 4.2. Inside of the container, all PMTs are connected to the high voltage supply and readout cables.

2. **Burning-in:** After all PMTs are in position and attached, the container is closed and locked. Then, the PMTs are supplied with their factory high voltage. The PMT has to deexcite, due to light exiting the photocathode of the PMT outside of the container. Over the following 12 hours, the dark count rate goes down to a ground state and measurements can start.

3. **First measurements:** In the first phase of measurements, the gain behavior of every PMT is measured. For this measurement, light from a pulsed source at a fixed wavelength is used at an occupancy of ≈ 10%. This measurement, the gain function over high voltage, and the nominal high voltage is quantified for each PMT. Additionally, the TTS and late- and afterpulse probabilities are measured as a function of the high voltage. In a second measurement, the LED is illuminating the PMTs at a much higher luminosity. Different voltages are applied to the PMTs for measuring the dynamic range. Then, the gain-slope-index and saturation can be specified. As a crosscheck to the first measurement, the gain function is calculated again.

The third measurement is used to quantify the photon detection efficiency (PDE) of each PMT. The PDE is measured relative to reference PMTs in the setup. For the illumination of PMTs, a light source with different wavelengths is used and allows the PDE measurement at different wavelengths.

All measurements are performed at room temperature. Each waveform is acquired and an external trigger is used for the readout. The setup is explained further in section 4.

4. **Cooling:** Over the next hours, the container is cooled down to -30°C. Meanwhile, the dark count rate is monitored. Due to an irregular cooling process of all PMTs, the rate...
can differ between the PMTs. After the temperature has stabilized for more than one hour, long noise rate measurements start and run over night. In the early morning, the cooling unit is turned off.

5. 2nd measurements: In front and behind the PMTs, a reflective canvas is placed. This canvas is to reflect emitted photons from PMTs or electronics. During slow reheating, the noise rate, afterpulse rate, and the gain are monitored. In addition, the noise signals are checked for any correlation of PMT clusters induced by light emitting bases or dynode systems.

6. Unloading: When all measurements are done the unloading begins. To avoid the condensation of humidity in the container, all PMTs have to be at room temperature. The next PMTs are loaded into the container before the tested PMTs are unrigged from their holding structure.

3.3 System overview

This section provides an overview of the planned and existing parts of the acceptance test facility. The basic components will be characterized in detail in chapter 4.

Figure 3.2 shows an overview of the setup. Inside of the container, the PMTs are located in a shelf-like structure. The required high voltage for the operation is provided by a power supply, located outside of the container with all other electronics. The data acquisition (DAQ) digitizes the waveforms of each PMT and feeds the data into a computer. This controls all electronic components and provides a live visualization of the data taken. The final analysis and data storing is done by a server. The light source is located outside of the container to prevent any temperature dependent effects. Light is fed into the container with an optical fiber. The fiber ends in a light integrating sphere [12] which integrates the light over solid angle and leads to a uniform illumination of the PMTs.

![Figure 3.2: Schematic overview of all acceptance test facility components.](image)
This chapter presents all components of the acceptance test facility setup, located in Aachen, Germany. The mechanical components are discussed in the first sections. All components in the container have to resist the cold temperatures inside. Furthermore, the function and structure of electronic and optical components are explained.

### 4.1 The container

For a few years, the IceCube working group in Aachen has had a 20ft shipping container. Equipped with an internal cooling unit, the container is able to cool down to -30°C [27]. The container has an additional thick isolating layer made out of polymer. In combination with an external cooling unit, the temperature can reach down to -50°C [27]. Figure 4.1 shows the front side of the container. The light sources are located on top of the container. Readout and supply electronics are located on the left side of the container together with a working place.

The container has been used for various measurements in the past, such as a study of acoustic signal induced by neutrinos in ice [28] or the final test of the IceAct telescope’s heating system [29].

By using the existing container for the acceptance test facility, a side focus is laid on the re-usability of the container in future experiments.

Figure 4.1: Open, isolated 20ft ISO shipping container in Aachen. The container is equipped with two cooling units. The standard unit can reach temperatures down to -30°C. The second additional unit can cool the container down to -50°C [27]. Taken from [28].
4.1.1 Moisture barrier

The humidity in the container decreases strongly when the container is running on very low temperatures. Water vapor freezes out and gathers on the metal walls. This causes a slip-stream of air into the container, if there is a hole or while opening the door. To prevent humid air rushing into the container while opening the doors, a moisture barrier has been installed. This wooden wall is located behind the entrance door of the container. The room between the barrier and doors of the container is used as a double door system. During normal operation in the two-day cycle, the condensation should not appear, but for the commissioning and adjustments, the barrier is important.

4.1.2 Feed-through

Most of the electronics and optical devices are outside of the container. To feed the high voltage cables, signal cables, and the optical fiber into the container, two holes are used. One hole is located in a wall next to the working place. Aluminum taped pipes are used for the feed-through to prevent light from reaching inside. On the outside of the container, the pipes are bend to the floor. Inside of the container, the pipes form a U-shape, displayed in Fig. 4.2. The shape has two benefits: Light is not able to trespass this barrier and humidity condensates on the pipe’s walls. In addition, the empty spaces inside the pipe are filled up with cloth to prevent air from rushing in.

The other hole is straightly placed through the ceiling and provides a feed-through for the optical fiber as well as for a BNC cable for the calibration of the coupling. Due to the minimal bending radius of the fiber, a U-shaped barrier is not possible for this penetration. The implementation was done by using 3D-printed clamps. Two different clamps were designed and printed. The clamp, located on the outside of the container, wedges the fiber and BNC cable and seals the penetration of the container. The clamp on the inside of the container has a lip to seal the down-going pipe to be impenetrable by light.

4.1.3 Wall cladding

To avoid any light reflections at the walls, as discussed in section 5.2, the walls of the container were clad with light-absorbing cloth. This cloth was tested for temperature stability and transparency before its installation in the container. All cloth pieces were equipped with eyelets and were fastened onto hooks with wires.
4.2 The "Vogelstange"

The time needed for loading and unloading all PMTs should be as short as possible. Due to efficiency, the holding structure is designed as a drawer for a shelf. Caused by the outer appearance of the drawer with the PMTs on top, it is called "Vogelstange" and a technical drawing is shown in Fig. 4.3. The "Vogelstange" is 1.54 m long and 0.6 m wide and can hold up to twelve PMTs. The required minimal distance between two PMTs is estimated as 20 mm which is ensured by fixed positions of the holding structures on the "Vogelstange". Each PMT is mounted to the "Vogelstange" outside of the container. Moreover, the changing time in the container is reduced by preparing all "Vogelstangen" outside. Only cables have to be connected inside. The PMTs are placed into a 3D-printed polylactic acid (PLA) holding structure. Fig. 4.4 shows a rendered view.

The 3D-printed holding structure is designed to be able to hold a 3.5" and 3" PMT. The structure is made out of PLA which can resist low temperatures, is humidity-stable, and non-magnetic. The plastic is electrically isolating and mechanically stable. Light from the dynode system can escape through the holes of the PLA structure, which implies a lower amount of materials required. The PLA structure can be scaled up for mass production. Furthermore, the structure is easy to mount and use in the setup.

The structures are constructed with additional spacers to keep the neighboring PMT at a safe distance. The spacers on the bottom of the structure provide a fixed alignment in the ITEM profile. The holder is fixed to the aluminum extrusions using two screws and counterparts in the rail. The spacer on top of the PLA structures provides enough space to the upper "Vogelstange". The upper and lower part of the PLA structure are screwed together. This ensures the easy mounting and an easy and solid positioning of the PMT.

![Figure 4.3: Design of the "Vogelstange". It consists of three combined 40 mm x 80 mm aluminum extrusions (grey). The PMTs (yellow) are placed in 3D-printed holding structures (blue). One "Vogelstange" can hold up to twelve 3.5" PMTs. All dimensions are in mm.](image-url)
Figure 4.4: On the left a close-up from Fig. A.2 is shown. All PMTs (yellow) are placed in a 3D-printed PLA structure (blue) which is shown on the right in a rendered view. The shelf structure consists of aluminum extrusions (grey). All dimensions are in mm.

4.3 Shelf structure

To store nearly 100 PMTs in the container, eight "Vogelstangen" are stacked on top of each other. The supporting frame is made out of 40 mm x 80 mm ITEM profiles and is fixed to the container. A close-up view of the stacked "Vogelstangen" is shown in Fig. 4.4. The whole technical drawing is shown in Fig. A.2 in the appendix. The "Vogelstangen" are placed on two ITEM profiles which act as rails and are placed in a vertical distance of 140 mm. Brackets are mounted at the head of each rail, preventing the "Vogelstangen" from sliding beyond the position. The whole shelf is 2.2 m in height, 1.62 m in width, and 0.6 m deep. On the top and the bottom, there are supporting frames for additional stability. The "Vogelstangen" are inserted into the shelf from the entrance of the container. Further, the "Vogelstange" is pushed to the end of the shelf’s rail and fixed in position with two screws.

4.4 Mechanics

The final design of the aluminum extrusions structure was done in collaboration with the workshop of the III. Physikalisches Institut B. On both ends, notches made out of PVC were added for keeping track of the rails in the ITEM profile. By applying screws into the notches the "Vogelstangen" are fixed in place. On the front of the shelf’s rails, stoppers, made out of PVC, were installed to prevent the "Vogelstange" from falling down. To fasten the whole shelf structure with the container, angle pieces were installed on each corner. After the shelf was aligned to the container, screws were added to fix the shelf in place.
4.4 Mechanics

(a) 3D-Printer

(b) PLA structure with PMT

Figure 4.5: On the left, the 3d printer used here belonging to the institute is shown. On the right side of the printing bed, three rails are shown and on the left side of the printing bed, three top spacers are shown. The finished assembled structure is shown together with a PMT on the right.

4.4.1 3D-printer

A 3D-printer is able to construct a computer designed structure by stacking layers of material onto each other [30]. Each layer has a height of around 0.2 mm. This differs depending on used material and printer used [30]. To reduce the amount of material used, the structures have a filling density of 20%. Inside of enclosed volumes, a grid shaped structure provides stability and material savings.

The holding structures of the PMTs were designed with the CAD\(^1\) software "Inventor 2019". The whole structure is divided into four parts. These are printed and then assembled. The first prototypes were printed with a 3D-printer of the institute, a Prusa i3 MK2\(^2\). This printer is suitable for the construction of prototypes. Only the first few structures were printed here. In Fig. 4.5 on the left side, the printer is shown while printing parts of the structure. The printing of one structure takes eight hours. By printing the same parts in parallel and over night, this time can be reduced to 6 hours.

To get experience with a large scale production of holding structures, connections with the FabLab\(^3\) of the computer science department at the RWTH Aachen University where established. Alongside their main focus of providing a non-profit workshops for students, they are able to provide a few professional 3D-printers for larger scale production [31].

4.4.2 Assembling

The bottom part of the holding structure is glued to a rail, which is displayed in Fig. 4.6 on the right hand side. The rail preserves the minimal safe distance between two PMTs inside of holding structures and supports the direction in which the PMT is facing. The top spacer is glued onto the top part of the holding structure. Afterwards, the plastic surface of the holding structure, which touches the PMT, is covered with foam tape. This tape prevents the glass

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\(^1\)Computer-Aided Design

\(^2\)https://www.prusa3d.de/

\(^3\)Fabrication Laboratories https://hci.rwth-aachen.de/fablab
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Figure 4.6: Above, a fully assembled PMT inside of a holding structure (blue) is shown. The passive base and high voltage connector are secured with the base holder (red).

surface from touching the plastic.

The parts are screwed together with two 65 mm long screws. This screw is fastened by a nut, which is placed into the bottom part with thread and then secured with glue. This leads to a stable and reusable connection.

After the structure is assembled, it is placed on a "Vogelstange" in its fixed position, shown in Fig. 4.6. The flying leads of the PMTs manufactured by Hamamatsu exceed the diameter of the aluminum extrusion. The base has to be placed on the ends of the flying leads.

4.4.3 Base holder

To place the PMT’s base directly behind the PMT, a base holder was designed. It consists of one 3D-printed angle piece, holding two 3D-printed shells. These shells are designed to hold the base of the PMT. All parts are screwed together and placed behind the holding structure. The base holder provides a solid support for the base and high voltage socket, which is particularly essential for the applied high voltage cable and the signal cable.

Figure 4.7: Above, the circuit diagram of the used passive base used is shown. The dynodes are equally supplied over a high voltage divider, except the first dynode which gets the doubled voltage.
4.4.4 Passive base

The passive bases used for the commission setup were designed by the IceCube working group in Erlangen. The circuit diagram is displayed in Fig. 4.7. They divide the high voltage in a ratio of 2:1:1:1:1. This means that the voltage between the Photocathode and first dynode is doubled in comparison to the voltages in the dynode chain. All bases were soldered and equipped with a high voltage connector for being able to connect a secure high voltage (SHV) cable to the base. The socket is placed into a 3D-printed plate, faced on four base spacers, as shown in Fig. 4.6. The plate has the same size as the printed circuit board. All screws and nuts used are made out of plastic to prevent any buildup of static charge.

4.5 Electronics

The electronics used of the acceptance test facility are located next to the container. This ensures a constant temperature for all electronics. In the final setup, the mDOM mainboard is used for the digitization. A CAEN V 1730 FADC [32] is used for the commissioning of the setup, because the first prototype will be constructed in late 2019 [26]. This, FADC is presented in the next section. Afterwards the light sources used are presented.

4.5.1 FADC CAEN V 1730

A CAEN FADC V 1730 is used in the Aachen setup. This FADC has 16 input channels [32]. These channels are digitized with 14-bit resolution and at a rate of 500 MHz [32]. In other words, the input range is digitized over 16384 values between the lower and higher boundary each 2 ns [32]. This value is called Analog to Digital Converter (ADC) count. The socket used is a MCX coaxial connector [32]. The FADC has a selectable dynamic input range of 0.5 or 2 Vpp (±0.25 or ±1 V) [32]. In addition, a DC offset can be applied. The FADC can read waveforms with up to 655360 samples, equal to a length of 1.31 ms [32]. The FADC is connected and powered over a VME 64 interface, and has an optical link interface for communications via an optical fiber [32]. The optical communication can provide a data transfer rate of up to 80 MB/s [32]. The FADC can either be triggered by an external trigger signal or programmable internal trigger [32]. The internal trigger can be adjusted for over/under thresholds for either common or individual trigger generation for each channel [32]. The external trigger is fed into the FADC over a LEMO socket and can either be a NIM⁴ or TTL⁵ pulse. The software trigger can be applied by a computer. In section 5.1, the commissioning and noise behavior is presented.

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⁴Nuclear Instrumentation Standard, negative logical pulse  
⁵Transistor-Transistor Logic, positive logical pulse
4.5.2 Wavedump

The FADC can be read out via the VME back plane together with a VME USB bridge or via optical fiber and an optical bridge module. Both configurations were tested and the latter was chosen in order to achieve a data transfer rate as high as possible. The software package Wavedump\(^6\) provided by CAEN is used for the first measurements. This software package is a C based readout tool. Different measurements can be performed by providing a configuration file. It is possible to automate the readout in the future. Wavedump connects to the FADC, does onboard calibrations, transfers data, and writes data files. The tool can write text or binary files. For the first applications, binary files where chosen due to the faster writing speed. In the configuration file, most properties of the FADC are declared. Beside the trigger configuration, sample length, and rate, the input range can be set.

4.5.3 Power supplies

In the first phases of the commissioning of the acceptance test bench, passive PMT bases are used. For the operation of a PMT, a high voltage has to be provided externally when using a passive base. In the setup, two high voltage supplies are used. The four channel supply N1470 \(^3\) and the twelve channel supply A7030 \(^4\), both manufactured by CAEN, are used. The data sheets predict a high voltage accuracy of $\sigma_{HV} < 1\text{ V}$. Both can be controlled over command line tools. In future the PMTs are operated with an active base.

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\(^6\)https://www.caen.it/products/caen-wavedump/

![Light sources and POCAM](image)

(a) Light sources  
(b) POCAM

Figure 4.9: On the left, the filter wheel with attached LEDs and coupling lens is shown. The light is coupled with the optical fiber which leads into the container. The fiber leads to a light integrating sphere \(^1\), which is shown on the right, inside of the container.
4.6 Light sources

In the setup, different light sources are used for different applications. A laser is needed for calibration of the optical components, pulsed LEDs for PMT measurements, and DC light sources for a larger wavelength coverage for QE measurements.

As a pulsed light source, LEDs are used, which are driven by an adjustable picosecond pulser \[35\], shown in Fig. 4.11. There, different parameters like the repetitive frequency of pulses, the bias voltage, and a trigger source can be chosen. The light output of the LED is adjustable via the bias voltage. The pulser is capable of producing light pulses with a standard deviation shorter than 1 ns \[35\]. This is needed for precise timing calibrations of the PMTs. The device is controlled over a USB connection. The LED driving signal is transferred to the LEDs using a coaxial cable. As shown in Fig. 4.9, the coaxial cables are connected to the back of the LED bases. They are located inside a filter wheel powered by a servo motor. This servo motor, a DYNAMIXEL XL-320 \[36\], is controlled and powered by an Arduino\(^7\) board. Similar to the pulser, this allows an operation over a command line. The motor has a step resolution of 0.29° \[36\]. In this configuration, the filter wheel can hold up to five different light devices, currently one laser (532 nm) for adjustments, and four LEDs (375 nm, 405 nm, 480 nm, 545 nm) for measurements.

The light sources are coupled into an optical fiber with a diameter of 910 \(\mu\)m via a coupling lens \[28\]. While the fiber has a fixed position, the lens can be adjusted in three directions. For the calibration of the lens position, a photodiode is mounted to the end of the fiber in the container. The signal is displayed on an oscilloscope next to the light setup.

The positioning and calibration of the optical components is done by the following steps:

1. In the first step, the lens is adjusted in the beam direction. For this, the laser is placed in front of the lens and in the middle of the beam line. Then, the lens is displaced until the measured voltage in the oscilloscope reaches the maximum. This is the case if the lens's focal point is slightly inside of the fiber \[28\]. Afterwards, the laser is placed into the filter wheel.

2. The position of the filter wheel is fixed over alignment with a pinhole and an adjustable aperture in front of the lens as shown in Fig. 4.10. Then, the filter wheel is rotated to three different positions and the alignment is checked. If necessary, the alignment is corrected and checked again. Afterwards, the pinhole and aperture are removed.

3. To adjust the lens, the vertical direction is changed first. The intensity of the injected light into the fiber follows a plateau-like shape depending on the displacement \[28\]. The lens is positioned in the middle of the plateau. If the plateau is not found in the first place, the lens is slightly shifted in horizontal direction and the procedure is repeated. When the vertical direction of the lens is set in the middle, the horizontal direction is checked for the plateau. In the same way as before, the lens is placed into the middle of the plateau.

Afterwards, all LEDs are tested at full intensity and the coupling of the fiber is completed. For different measurement, DC light is needed. The light can be provided by LEDs which are operated over a voltage supply. This voltage supply can be operated via command line.

\(^7\)https://www.arduino.cc/
Chapter 4 Setup

4.6.1 Light integrating sphere

To diffuse the light inside the container, a light integrating sphere is used. The sphere was built for the POCAM module in the IceCube Upgrade [12]. This sphere is made out of semi transparent Teflon [12]. By using Lambertian reflections, the light pulses are isotropically distributed over the solid angle [12]. Hence, any effects of the optical fiber are corrected.

4.6.2 Final setup

In Fig. 4.12, a picture of the final setup is shown. Four "Vogelstangen" with four PMTs each are located inside of the shelf. The used PMTs are listed in table 4.1. For the commissioning of the setup, twelve PMTs are borrowed from the Münster working group. In addition, four PMTs from the Aachen working group are used. In front of the PMTs, the POCAM is located. The metallic walls are covered with light absorbing cloth and the moisture barrier is in the back of the shelf towards the entrance of the container.

Table 4.1: List of all available PMTs

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Diameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu</td>
<td>R12199-01HA</td>
<td>3&quot;</td>
<td>6</td>
</tr>
<tr>
<td>HZC Photonics</td>
<td>XP82B2F</td>
<td>3.5&quot;</td>
<td>6</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>R12199</td>
<td>3.1&quot;</td>
<td>1</td>
</tr>
<tr>
<td>HZC Photonics</td>
<td>XP72B20</td>
<td>3.1&quot;</td>
<td>1</td>
</tr>
<tr>
<td>ET Enterprises Ltd</td>
<td>9320KFLB</td>
<td>3&quot;</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 4.12: Final 16er setup. All walls are clad with light absorbing cloth and four "Vogelstangen" are placed into the shelf with four PMTs each. In front of the PMTs, the POCAM is located.
In the following chapter, the commissioning of the acceptance test facility is described in detail. In section 5.1, the calibration and commissioning of the FADC is described. Further, the light output of the POCAM is measured and analyzed in section 5.2. The current setup is explained in section 5.3, then the first PMT measurements are presented in section 5.3.

Due to missing safety installations, it was not able to operate the container at negative temperatures. The installation of an emergency exit is planned for the end of 2019.

5.1 FADC calibration and noise measurement

Before using the FADC as a digitizer, the noise and calibration has to be studied. The input stage of the CAEN V 1730 is shown in Fig. 5.1. The analog input signal is fed into one of two software selectable amplifiers [37]. Then, a DC offset can be added to the signal and is chosen in ADC counts [37]. The applicable offset voltage ranges from -1 V to +1 V [37]. Afterwards, the signal is digitized in a differential analog-to-digital converter (ADC) [37]. To achieve a sampling rate of 500 MS/s, two time-interleaved 250 MS/s unit ADCs are used [37]. The Intersil Interleave

![Figure 5.1](image)

Figure 5.1: Above, the analogue input stage of the x730 digitizer family, manufactured by CAEN, is shown. It has two input amplifiers which can be chosen by the readout software. After the amplifiers, a DC offset is applied and the signal is digitized via a differential ADC [37]. Taken from [37].
Engine (I2E) automatically corrects for offset, gain, and time mismatches of the two ADCs [37]. Furthermore, it adjusts temperature and voltage variations for each individual channel in real-time [37].

The FADC runs an auto-calibration on each power up [37]. This happens independent of any incoming signal because the ADCs have electronic switches which disconnect the inputs from the internal circuit during calibration [37].

To study the noise behavior of the FADC, baseline measurements were performed. These measurements were performed with the same settings as proposed for the PMT measurements. With an external trigger applied into the "Trigger IN" channel, 100 k waveforms with 640 samples each were taken. The readout of the FADC was performed via an optical fiber and controlled over the readout software Wavedump provided by CAEN [37].

Fig. 5.2 shows exemplary result of channels 2 and 6. The histograms display all samples of the noise measurement after the onboard calibration. A Gaussian was fitted to the data which successfully estimates the shape. The results of all channels are shown in section B of the appendix.

In Tab. 5.1, the calculated results of the noise measurement are shown for all channels. All channels have a standard deviation of around two ADC counts as estimated from the Gaussian. However, the channels differ slightly in their baselines so these have to be corrected individually in further measurements.
5.2 Homogeneity of the integrating sphere

The light sources are located on top of the container and the light is fed into the container via an optical fiber. To be able to measure more than one PMTs at the same time, the light has to be equally distributed. To achieve an equally illuminated surface, a light integrating sphere is used and set as far away as possible from the PMTs. In the container, this distance is limited by the container’s depth.

To verify the homogeneity of the integrating sphere, a 2 m wide canvas is placed in front of the PMTs. Then, the adjustment laser is turned on and a picture is taken with a camera, placed slightly behind the integrating sphere. The setup is shown in Fig. 5.3. The camera used is a Canon 1000 D\(^1\) together with a EFS 18 – 55 mm\(^2\). The resulting raw picture is separated into the three colors of the sensor. Due to the sharp wavelength spectrum of the laser, only the green channel is used for the analysis. The red and blue channels are showing only noise and little residual light. This ensures an undisturbed measurement. The exposure time is 30 sec. The blue and red channels are shown in section C of the appendix.

For the verification of the relative intensity at the PMT positions, the shift in intensity of the camera’s optics has to be corrected. This is done in order to get the relative intensity on the canvas. For this correction an array of correction factors is calculated in the dimensions of the picture in pixel. Then the correction array is multiplied with the green channel of the raw image. For the estimation of intensity per area, the following equation is used.

\[
I_2 = \frac{I_0}{4\pi r_1^2} \cdot \cos^3(\alpha) \quad (5.1)
\]

\(I_2\) is the intensity per area on the quasi pixel area \(A_2\), as shown in Fig. 5.4. The intensity \(I_0\) in the quasi pixel area \(A_1\) is normalized to one. \(r_1\) is the horizontal distance of the POCAM to the canvas and \(\alpha\) the angle between the center of area \(A_1\) and \(A_2\). The intensity follows a cosine dependency of the third power. This is a consequence of a square dependence to the

\(^1\)https://www.canon.de/support/consumer_products/products/cameras/digital_slr/eos_1000d.html
\(^2\)https://www.usa.canon.com/internet/portal/us/home/products/details/lenses/ef/standard-zoom/ef-s-18-55mm-f-3-5-5-6-is-ii
Chapter 5 Commissioning

Figure 5.3: Setup for homogeneity measurement. In front of the PMTs, a canvas is placed to reflect the light coming from the light diffuser. Right above this diffuser, a camera is located, facing the canvas. A long exposed picture is taken for the measurement.

Figure 5.4: Sketch to equation 5.1.

distance and the tilted area.

By normalizing the image with the highest value of the canvas, the relative intensity is calculated. The result is shown in Fig. 5.5. Except for a few artifacts due to reflection at the metallic walls, the intensity shows a small decrease from the middle to the outer regions. The reflection of the walls is later on prevented by hiding them behind light-absorbing cloth.
5.3 First light

With all components in place and working, the first light measurements were done. In the following, the analysis is presented and therefore 12 PMTs are tested in parallel to get confidence in the setup. Table 5.2 shows the used configuration. The results are shown in the following for the PMT in channel 0 (Hamamatsu R12199-01 HA). Plots for all 12 PMTs are located in section D of the appendix.

In the first measurements, a pulsed LED is used. The bias voltage is adjusted to achieve an occupancy of $\approx 10\%$. The applied high voltage is set to the factory nominal high voltage. The FADC is triggered via the light pulser trigger signal, which is acquired, as well. In an oscilloscope, the pulse height is checked to ensure a suitable range of the FADC. Due to the used sampling rate of 500 MHz, the measured pulse shape is not exact. A pulse shaper will be used on the mDOM mainboard in the further development of the test facility to achieve a better resolution.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Serial No.</th>
<th>Channel</th>
<th>Type</th>
<th>Serial No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 0</td>
<td>R12199-01 HA</td>
<td>BA 0580</td>
<td>Ch 6</td>
<td>XP82B2F</td>
<td>7201048</td>
</tr>
<tr>
<td>Ch 1</td>
<td>R12199-01 HA</td>
<td>BA 0582</td>
<td>Ch 7</td>
<td>XP82B2F</td>
<td>7201047</td>
</tr>
<tr>
<td>Ch 2</td>
<td>R12199-01 HA</td>
<td>BA 0584</td>
<td>Ch 8</td>
<td>XP72B20</td>
<td>7201045</td>
</tr>
<tr>
<td>Ch 3</td>
<td>R12199-01 HA</td>
<td>BA 0585</td>
<td>Ch 9</td>
<td>9320KFLB</td>
<td>-</td>
</tr>
<tr>
<td>Ch 4</td>
<td>XP82B2F</td>
<td>7201042</td>
<td>Ch 10</td>
<td>R12199</td>
<td>-</td>
</tr>
<tr>
<td>Ch 5</td>
<td>XP82B2F</td>
<td>7201041</td>
<td>Ch 15</td>
<td>R12199-01 HA</td>
<td>BA 0586</td>
</tr>
</tbody>
</table>

Table 5.2: PMT configuration of the first light measurements
5.3.1 Waveform calibration

In Fig. 5.6a, a single raw waveform for a Hamamatsu R12199-01HA at factory voltage is shown. For this analysis, all waveforms are inverted, so that the pulses are positive. The occurrence of a pulse in a waveform is checked using a constant threshold discriminator (CTD) with a threshold of $U_{\text{threshold}} = 11$ ADC counts $= 1,342$ mV. This value is chosen by excluding FADC noise with five standard deviations. After correcting the baseline by subtracting the mode of the first 250 samples, the ADC counts are converted to mV by applying the following equation.

$$U[\text{mV}] = U[\text{ADC}] \cdot 1000 \frac{\Delta U(\text{FADC range})[V]}{2^{14}\text{bit}}$$  \hspace{1cm} (5.2)

$U[\text{mV}]$ is the desired voltage, $U[\text{ADC}]$ the measured ADC count of the FADC, $\Delta U(\text{FADC range})$ the chosen voltage range of the FADC.

5.3.2 Single photoelectron spectrum

For the first analysis, more than one pulse is needed to construct the SPE spectrum. Hence this, the charge of each waveform, independent of a signal, is calculated by taking the sums of the samples over an interval around the pulse. The charge is estimated by:

$$Q = \frac{1}{R_{\text{impedance}}} \sum_{t_{\text{pulse}}-20\text{ns}}^{t_{\text{pulse}}+50\text{ns}} U(t)$$  \hspace{1cm} (5.3)

$R_{\text{impedance}}$ is the impedance of the base and $t_{\text{pulse}}$ is estimated as a constant value at $t_{\text{pulse}} = 585$ ns. In section 5.3.5, the stability of this time is confirmed. This time window appears to be suitable for the SPE estimation, when comparing to measurements done by others [22]. Then, all charges are displayed in a histogram, as shown in Fig. 5.6b. For the estimation of the 1 PE and 2 PE peak, fits were applied to the data. The two PE signals are induced due to the Poisson statistics process of the light emission. The red fit curve is a composite fit out of three...
Table 5.3: Results of the SPE spectrum analysis

<table>
<thead>
<tr>
<th>Channel</th>
<th>P/V ratio</th>
<th>$\sigma_{SPE}$ (PE)</th>
<th>$U_{nom}$ [V]</th>
<th>Channel</th>
<th>P/V ratio</th>
<th>$\sigma_{SPE}$ (PE)</th>
<th>$U_{nom}$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 0</td>
<td>2.02</td>
<td>0.41</td>
<td>1142</td>
<td>Ch 6</td>
<td>none</td>
<td>none</td>
<td>1012</td>
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<tr>
<td>Ch 1</td>
<td>1.83</td>
<td>0.49</td>
<td>1069</td>
<td>Ch 7</td>
<td>1.09</td>
<td>0.89</td>
<td>1147</td>
</tr>
<tr>
<td>Ch 2</td>
<td>2.35</td>
<td>0.44</td>
<td>1067</td>
<td>Ch 8</td>
<td>2.83</td>
<td>0.38</td>
<td>1149</td>
</tr>
<tr>
<td>Ch 3</td>
<td>2.17</td>
<td>0.42</td>
<td>1085</td>
<td>Ch 9</td>
<td>2.42</td>
<td>0.40</td>
<td>1040</td>
</tr>
<tr>
<td>Ch 4</td>
<td>1.81</td>
<td>0.60</td>
<td>1061</td>
<td>Ch 10</td>
<td>2.78</td>
<td>0.41</td>
<td>1291</td>
</tr>
<tr>
<td>Ch 5</td>
<td>1.89</td>
<td>0.52</td>
<td>1160</td>
<td>Ch 15</td>
<td>2.18</td>
<td>0.40</td>
<td>1007</td>
</tr>
</tbody>
</table>

different Gaussian functions. The first Gaussian is used to estimate the pedestal and, therefore, the mean is therefore set to zero. The second Gaussian is estimated to describe the SPE peak. The mean of the third Gaussian is set to the double value of the second Gaussian.

From the fit function, the peak-to-valley ratio and gain are estimated. For the peak-to-valley ratio, the maximum of the SPE peak is divided by the value of the local minimum of the data points. For the displayed PMT the peak-to-valley ratio is $P/V = 2.02$ and the SPE resolution is $\sigma_{SPE} = 0.41 \pm 0.09$ pe. The error is estimated by the standard deviation of the fit of the pedestal. Because the pedestal represents waveforms only with noise, the standard deviation is an expressive value of the charge estimation. Within the error, the value is compatible to other measurements [22]. The gain is calculated by dividing the charge of one PE by the elementary charge. In table 5.3, all measured values are displayed. For the PMT on channel 6, the SPE spectrum does seem to deviate in comparison to the one shown in 5.6. In section 5.3.6, this poorly working PMT is further discussed. Plots for all PMTs are located in section D of the appendix.

![Figure 5.7: The gain over high voltage plot for the PMT at channel 0 is shown. The nominal gain of $5 \cdot 10^6$ is reached at 1142 V and is estimated by a powerlaw regression.](image)
Figure 5.8: On the left, a plot with 474 raw waveforms is shown. All waveforms are plotted in black, the average waveform (red) does not describe the waveforms shape properly due to time shifts between the raw waveforms. Here, the dataset of five thousand waveforms, 474 with a pulse, is displayed as in Fig. 5.12. The sketch shows all features of a PMT pulse needed for the calculation of $t_{50}$. The CFD calculates via linear interpolation the time where the pulse reaches 50% of its height. The $\sigma_{\text{CFD}}$ is calculated by the fraction of the slope of the linear fit over the baseline's standard deviation and represents the error of the CFD.

5.3.3 Nominal high voltage

The analysis of the SPE spectrum is repeated at different high voltages. Then, the values for the gains are plotted logarithmically over the applied high voltage and is illustrated in Fig. 5.7. The single data points are fitted with a powerlaw regression. The nominal voltage is estimated by the intersection of this regression with a gain of $5 \cdot 10^6$. The displayed result for the Hamamatsu R12199-01HA (channel 0) has the nominal gain at $U_{\text{nominal gain}} = 1142$ V. An error can be estimated via the fit function, but is useless for further measurements because only fixed values can be applied to the high voltage supply. The plots for all PMTs are located in section D of the appendix.

5.3.4 Average waveform

The calculation of the average waveform is not trivial. As shown in Fig. 5.8a, the average is not representative in shape and height in comparison to a single waveform, as shown in Fig. 5.6. The time shift between the individual waveforms is induced by two major effects. To display the progress of calculating the average waveform, only five thousand waveforms are analyzed out of the dataset. With the CFD and the condition to have only one PMT pulse in the waveform, 474 out of these five thousand waveforms were chosen.

The first effect is the instability of the recorded trigger waveform. A single waveform is shown in Fig. 5.9a. The shift in position can be seen on the right hand site where 20 rising edges are displayed in Fig. 5.9b. This shift occurs due to different time offsets in the FADC readout. The rising edges, which the FADC uses for triggering, have a shift in FADC bins of 7 sample counts or 14 ns. This is shown in Fig. 5.10a. The time differences are induced by shifts in the internal clockcycle. The internal clocks runs with 50 MHz which would match with
5.3 First light

(a) Single trigger pulse shape  
(b) Rising edges of 20 trigger pulses

Figure 5.9: The single trigger waveform has a steep rising edge with approximately two to three data point. A close up of the rising edges of 20 waveforms is displayed on the right. They are taken from one measurement and represent just a small bin shift. The rising edges have a time shift in between each other. This effect is corrected by estimating the $t_{50}$ of each trigger pulse.

the maximal time difference [32]. For the correction of this effect, the exact time of the rising edge has to be calculated. A CFD is implemented in software to achieve this. In Fig. 5.8b a sketch of the CFD is shown. This discriminator fits a linear function to the rising edge. For this regression, all data points in the rising edge between 15% to 92% of the maximal value of the pulse are used. This range is motivated by excluding the baseline and taking only the first value of the plateau with an additional steep required slope to the prior data point. By calculating the intersection with the 50% level on the rising edge, $t_{50}$ is estimated. For the error estimation of the CFD, the error is calculated as:

$$\sigma_{\text{CFD}} = \frac{\sigma_{\text{Baseline}}}{\text{slope}_{\text{linear fit}}} \quad (5.4)$$

Figure 5.10: The trigger time shift of the trigger pulse is displayed in a histogram with 100k entries. The $t_{50}$ of the rising edge is nearly discretely uniformly distributed. The error of the CFD of the trigger signal is shown. The value of $\sigma_{\text{CFD (Trigger)}} = 2.91 \text{ ps}$ confirms that the time estimation of the CFD is producing reasonable results.
Figure 5.11: The time shift of PMT pulses is shown. Prior to the estimation of $t_{50}$ of the PMT pulses, the waveform was corrected for time shifts of the trigger. Then, the absolute time difference to a reference point in the waveform is calculated. The errors of the CFD are displayed on the right hand side. The mean is estimated to $\mu = 0.16$ ns which concludes a good time resolution beside the binning error of the FADC with $\sigma_{FADC} = 0.577$ ns.

This equation displays the connection between the baseline noise behavior $\sigma_{Baseline}$ and the fitted slope [38]. The results for the error of the CFD in the trigger signal are shown in Fig. 5.10b. The value of $\sigma_{CFD \ (Trigger)} = 2.91$ ps confirms that the implementation in the software produces robust results. The dominating error for the time shift comes from the binning error of the FADC, given by $\frac{2\Delta t}{\sqrt{12}} = 0.577$ ns.

The correction is done by shifting the whole waveform by the difference of $t_{50}$ to a fixed reference point on the waveforms. After applying this correction, the waveforms are plotted together with the average in Fig. 5.12a. In comparison to the first plot, the result looks more promising.

The second effect is induced by the transit time spread of the PMT. Correcting for this effect

Figure 5.12: The trigger shift corrected waveforms are displayed. The shape is slightly improved comparing to before any correction, but not sufficiently. On the right, the transit time shift of the PMT pulses is corrected. This leads to an acceptable average waveform result. Here, the same dataset of five thousand waveforms, 474 with a pulse, is displayed as in Fig. 5.8.
5.3 First light

requires, similar to the previous one, a CFD. This time the rising edge of the waveform is much more narrow. Sometimes only two data points form the rising edge, including the maximum value. To prevent the linear regression from failing, a new method has been implemented. It searches for the rising edge and takes the data point directly in front and behind the estimated \( t_{50} \). The search is implemented by finding the first value above \( U_{50} \), then checking if the slope is positive and the pulse in the estimated time range between \( t \in t_{\text{estimation}} \pm 30 \text{ ns} \). Between these two points, the slope is estimated and the intersection at 50% of the maximal value is calculated, as displayed in Fig. 5.8b. The shifts are shifted to another fixed reference point on the waveform, similar to the previous one, and displayed in the histogram in Fig. 5.11a. Afterwards the whole waveform is shifted again.

The resulting shifted waveforms are displayed together with the average in the right plot in Fig. 5.12b. The average describes the waveforms in a proper way. The pulses’ lengths are in agreement, as well as the maximal height. The average waveforms for all PMTs are located in section D of the appendix.

5.3.5 Transit-time spread

The timing information of the PMT are gained by calculating the time difference between the trigger pulse and the PMT pulse. Due to the trigger shift correction, the trigger is on a defined position. To calculate the absolute time difference, the PMT pulse position is estimated by the previously discussed CFD.

The TTS is calculated by the time difference of the \( t_{50} \) (trigger) and the \( t_{50} \) (Pulse). These time differences are displayed in Fig. 5.13a. The peak can be fit with a Gaussian \([39]\). The standard deviation of the Gaussian is the TTS.

The resulting TTS of \( 2.5 \pm 0.16 \pm 0.57 \text{ ns} \) is compatible with the tender specification of the PMT. The first error of \( \pm 0.16 \text{ ns} \) comes out of the CFD error estimation. The second error \( \pm 0.57 \text{ ns} \) is deduced as the binning error of the FADC. The results for all PMTs are displayed in table 5.4. All PMTs in the setup have TTS in the region of the tender specifications. The plots for all PMTs are located in section D of the appendix.

![Transit-Time Spread](image)

(a) Transit-Time Spread

![Charge over transit-time spread](image)

(b) Charge over transit-time spread

Figure 5.13: All time differences between corrected trigger pulse and PMT pulse are displayed. The used fit function is a Gaussian. The calculated TTS of \( 2.5 \pm 0.16 \pm 0.57 \text{ ns} \) is compatible with the tender specifications of the PMTs. The pulse charge is plotted over the transit time in a 2D-historam. Here, most of the SPE pulses arrive simultaneously with the same charge.
Table 5.4: Results of the TTS measurements

<table>
<thead>
<tr>
<th>Channel</th>
<th>TTS [ns]</th>
<th>$\mu_{\sigma_{\text{TTS}}}$ [ns]</th>
<th>Channel</th>
<th>TTS [ns]</th>
<th>$\mu_{\sigma_{\text{TTS}}}$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 0</td>
<td>2.5</td>
<td>0.16</td>
<td>Ch 6</td>
<td>1.8</td>
<td>0.55</td>
</tr>
<tr>
<td>Ch 1</td>
<td>2.4</td>
<td>0.17</td>
<td>Ch 7</td>
<td>1.94</td>
<td>0.32</td>
</tr>
<tr>
<td>Ch 2</td>
<td>2.5</td>
<td>0.16</td>
<td>Ch 8</td>
<td>3.19</td>
<td>0.39</td>
</tr>
<tr>
<td>Ch 3</td>
<td>2.43</td>
<td>0.17</td>
<td>Ch 9</td>
<td>3.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Ch 4</td>
<td>3.0</td>
<td>0.29</td>
<td>Ch 10</td>
<td>2.04</td>
<td>0.17</td>
</tr>
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<td>Ch 5</td>
<td>3.01</td>
<td>0.29</td>
<td>Ch 15</td>
<td>2.73</td>
<td>0.18</td>
</tr>
</tbody>
</table>

In Fig. 5.13b, the charge per pulse is displayed versus the transit time. The pulses prior to the main pulses are carrying less charge than all other pulses. The main and late pulses carry the charge around one PE. The plots for all PMTs are located in section D of the appendix.

5.3.6 Analysis challenges

One PMT in channel 6 (HZC Photonics XP82B2F) shows a faulty behavior in the analysis. A single waveform and SPE spectrum are shown in Fig. 5.14. The pulse height is too low by a factor of four for the applied factory voltage of 1012 V. On the right, the SPE spectrum is shown. Due to the almost invisible SPE peak, it is not possible to calculate the nominal gain or any ratio. Only at higher voltages the SPE peak gets distinguishable from the pedestal. In the acceptance test this PMT would be sorted out and tested again with a different base.

Figure 5.14: The single waveform of the HZC Photonics XP82B2F on channel 6 is only a few ADC counts above the FADC noise. The pulse height is for the applied factory voltage of 1012 V too low by a factor of four. Due to the almost invisible SPE peak, it is not possible to calculate the nominal gain or any ratio. In the acceptance test this PMT would be sorted out and tested again with a different base.
With the construction of the IceCube Upgrade taking place in the Antarctic summer season 22/23, all PMTs used for the new light sensors have to be tested prior to assembly. A large scale acceptance test facility was developed for the huge amount of PMTs needed. By testing 100 PMTs in parallel, a tightly scheduled testing plan ensures reliable PMT operation in the Antarctic ice.

The concept was checked in practicability and a design of the facility was engineered. It should be located inside a 20 ft isolated shipping container and one testing run should not exceed two days. In these days all required measurements are performed to check the PMTs for the tender specifications and reject poorly or faultily operating PMTs. The design was realized in building the acceptance test facility, accompanied by improving the mechanical setup in terms of usability, and time optimization.

After all mechanical and electrical components were established, the optical setup was implemented and tested. Then, the digitization over a FADC was established and tested. In the future design, the FADC will be replaced by the mDOM mainboard. Many feasible improvements were considered and enabled for future implementations.

Within the commissioning of the facility, the FADC behavior, homogeneity, and coupling of the light source were quantified. Afterwards, the first light measurements were performed and analyzed to ensure a smooth transition to actual service. For this process, there are further steps require to be taken in the following months. Finally, the acceptance test facility will be operative and able to perform measurements.
Appendix

A ITEM shelf structure

Figure A.1: Technical drawing of the holding structure of PMTs for the acceptance test facility.
Figure A.2: Technical drawing of the mechanical shelf structure for the acceptance test facility.
B FADC calibration

Figure B.1: FADC noise analysis

FADC Noise Analysis
Appendix

FADC Noise Analysis

(a) Channel 6

(b) Channel 7

FADC Noise Analysis

(a) Channel 8

(b) Channel 9

FADC Noise Analysis
FADC Noise Analysis

(a) Channel 10

(b) Channel 11

FADC Noise Analysis

(a) Channel 12

(b) Channel 13

FADC Noise Analysis

(a) Channel 14

(b) Channel 15

FADC Noise Analysis
C Homogeneity measurement

Figure C.1: Blue raw channel of homogeneity measurement

Figure C.2: Red raw channel of homogeneity measurement
D Analysis plots

Single Photoelectron spectrum

Figure D.1: SPE spectrum
Appendix

(a) Channel 4

(b) Channel 5

SPE spectrum

(a) Channel 6

(b) Channel 7

SPE spectrum
(a) Channel 8

SPE spectrum

(b) Channel 9

SPE spectrum

(a) Channel 10

SPE spectrum

(b) Channel 15
Nominal high voltage

Figure D.2: Channel 0 - Gain over high voltage

Channel 1 - Gain over high voltage
Channel 2 - Gain over high voltage

Channel 3 - Gain over high voltage
Appendix

Channel 4 - Gain over high voltage

Channel 5 - Gain over high voltage
Channel 6 - Gain over high voltage

Channel 7 - Gain over high voltage
Appendix

Channel 8 - Gain over high voltage

Channel 9 - Gain over high voltage
Channel 10 - Gain over high voltage

Channel 15 - Gain over high voltage
Appendix

**Average Waveform**

![Waveform Diagram](image)

- (a) Channel 0 - 3584 WFs
- (b) Channel 1 - 3330 WFs

Figure D.3: Average waveforms

- (a) Channel 2 - 3688 WFs
- (b) Channel 3 - 3464 WFs

SPE spectrum
(a) Channel 4 - 4186 WFs
(b) Channel 5 - 4597 WFs

(a) Channel 6 - 51 WFs
(b) Channel 7 - 3478 WFs

SPE spectrum
Appendix

(a) Channel 8 - 4262 WFs
(b) Channel 9 - 4172 WFs

SPE spectrum

(a) Channel 10 - 3990 WFs
(b) Channel 15 - 3235 WFs

SPE spectrum
Transit-Time-Spead

Figure D.4: Channel 0 - Transit-time spread with CFD error

Channel 1 - Transit-time spread with CFD error
Appendix

Channel 2 - Transit-time spread with CFD error

Channel 3 - Transit-time spread with CFD error
Channel 4 - Transit-time spread with CFD error

Channel 5 - Transit-time spread with CFD error
Appendix

Channel 6 - Transit-time spread with CFD error

Channel 7 - Transit-time spread with CFD error

Channel 8 - Transit-time spread with CFD error
Channel 9 - Transit-time spread with CFD error

Channel 10 - Transit-time spread with CFD error

Channel 15 - Transit-time spread with CFD error
Appendix

**Charge over Time**

Figure D.5: Charge over transit time

Charge over transit time
Charge over transit time

(a) Channel 4
(b) Channel 5

Charge over transit time

(a) Channel 6
(b) Channel 7
Appendix

(a) Channel 8

(b) Channel 9

Charge over transit time

(a) Channel 10

(b) Channel 15

Charge over transit time


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<td>ADC</td>
<td>Analog to Digital Converter</td>
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<td>CFD</td>
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<td>DOM</td>
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<td>FADC</td>
<td>Fast Analog to Digital Converter</td>
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<td>FAT</td>
<td>Final Acceptance Testing</td>
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<td>HQE</td>
<td>High Quantum Efficiency</td>
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<td>ISO</td>
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<td>mDOM</td>
<td>multi-PMT digital optical module</td>
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<td>Photoelectron</td>
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<tr>
<td>pe</td>
<td>Photon equivalent</td>
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