Recent Developments with Microchannel-Plate PMTs

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Abstract

Microchannel-plate (MCP) PMTs are the favored photon sensors for the DIRC detectors of the PANDA experiment at FAIR. Until recently the main drawback of MCP-PMTs were serious aging effects which led to a limited lifetime due to a rapidly decreasing quantum efficiency (QE) of the photo cathode (PC) as the integrated anode charge (IAC) increased. In the latest models of PHOTONIS amd Hamamatsu an innovative atomic layer deposition (ALD) technique is applied to overcome these limitations. During the last five years comprehensive aging tests with ALD coated MCP-PMTs were performed and the results were compared to tubes treated with other techniques. The QE in dependence of the IAC was measured as a function of the wavelength and the position across the PC. For the best performing tubes the lifetime improvement in comparison to the older MCP-PMTs is a factor of >50 based on an IAC of meanwhile >10 C/cm^2. In addition, the performance results of a new 2-inch ALD coated MCP-PMT prototype from Hamamatsu with a very high position resolution (128x6 anode pixels) is presented and the first conclusions from investigations concerning the PC aging mechanism will be discussed.

Keywords: Cherenkov detectors, microchannel-plate photomultipliers, lifetime, atomic layer deposition (ALD)

1. Introduction

Multi-anode microchannel-plate photomultipliers (MCP-PMTs) were identified as the only suitable sensors for the DIRC detectors [1, 2, 3, 4] of the PANDA experiment [5] at the new FAIR facility at GSI. They are compact in size and allow the detection of single photons in high magnetic fields of >1 T with an excellent time resolution of <50 ps, while still showing a moderate dark count rate of <1 kHz/cm^2. Furthermore, they are capable of digesting the detected photon rate of ~200 kHz/cm^2 for the Barrel DIRC (BD) and up to 1 MHz/cm^2 for the Endcap Disc DIRC (EDD). However, these rates extrapolate to an integrated anode charge (IAC) of ~5 C/cm^2 for the BD and even more for the EDD, if one assumes running PANDA at a 50% duty cycle over 10 years with a PMT gain of 10^6. Just 5 years ago such an IAC was far beyond the reach of any commercially available MCP-PMT, for which the quantum efficiency (QE) had usually dropped to less than half of its original value at an IAC of <200 mC/cm^2 [6, 7, 8]. This is due to aging of the photo cathode (PC) presumably by ion feedback.

During the recent years several approaches were pursued to reduce the PC aging of MCP-PMTs: improved vacuum, cleaning of the MCP surfaces with electron scrubbing techniques, ultra-thin alumina films in front of or between the MCP layers [9], and modified and more robust PCs [10]. These techniques showed clear improvements in the lifetime of MCP-PMTs but the main breakthrough came with the application of an atomic layer deposition (ALD) approach, where the MCP substrate is coated with an ultra-thin layer of alumina or MgO. This technique was first applied by Arradiance Inc. [11] and then taken over by PHOTONIS and the LAPPD collaboration [12]. Meanwhile, also Hamamatsu and Photek [13] are using this approach to improve the lifetime of MCP-PMTs. With the ALD technique the MCP pores are coated by up to three layers of different materials: a resistive, a secondary electron emissive and an electrode layer. In this way the MCP resistance and the secondary electron yield (SEY) can be tuned independently and a higher gain compared to non-ALD tubes may be obtained at a given high voltage. In this proceedings only the performance of ALD coated MCP-PMTs will be discussed. For former results we refer to Refs. [8, 14, 15].

2. Properties of new Hamamatsu 2" MCP-PMT prototype

For the BD an anode pixel size of about 6×6 mm^2 is sufficient, while for the EDD a much higher position resolution with a pixel size of 0.5×16 mm^2 or smaller is needed to achieve the

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optimum Cherenkov angle resolution. For an optimal active area ratio a tube size of 2-inch squared is preferable. Two-inch PHOTONIS MCP-PMTs of the Planacon type are available since many years and can in principle be obtained with both anode pixelations.

Recently, Hamamatsu has also developed a squared 2-inch MCP-PMT in addition to their standard 1-inch MCP-PMT (R10754X-M16M). The first prototypes we received in 2014 with ALD coated MCP surfaces and a film in front of the first MCP layer. With 70% the active area ratio is somewhat lower than that of the PHOTONIS MCP-PMTs which is 81%. Currently, the new Hamamatsu 2-inch MCP-PMTs are available as 8×8 and as 6×128 pixel versions (R13266-M64 and R13266-M768). Since these position resolutions are suitable for the PANDA DIRCs, the performance parameters of the new Hamamatsu MCP-PMTs were investigated in detail.

Reading out the 6×128 pixel version with standard NIM and VME electronics proved as difficult. The backplane of this MCP-PMT consists of 12 blocks, each with 4×16 long anode pins with a 0.05” pitch. Because of this extremely high pin density special readout and adapter boards had to be developed before a characterisation of the tubes was possible. The solution were 4 separate multi-layer readout boards each covering three of the twelve 64-pin blocks. These boards were equipped with three 0.05” pitch FOLC-120-02-L-Q Samtec receptacles with 4×20 pins at one side and three 0.05” pitch LSHM-140-02.5-L-DV-A-S-TR Samtec receptacles with 2×40 pins at the opposite side. Through 80-channel coaxial cables with 2×40 pin plugs at each side these boards were connected to an additional adapter board with four 0.1” pitch 2×8 pins plugs which can be directly connected to standard NIM and VME electronics. In this way principially all 768 channels of the Hamamatsu R13266-M768 MCP-PMT can be read out simultaneously.

In Fig. 1 the main properties QE, gain, dark count rate, rate stability, cross talk, and time resolution are plotted. On the negative side we observe that the QE across the PC is not yet homogeneous enough, the gain is varying by almost a factor 10 across the active surface and the rate capability is with $<10^6$ photons/cm^2 lower than that of most other MCP-PMTs [15]. On the positive side we find a very low dark count rate of well below 100 Hz/cm^2 except at one hot spot, a good cross talk behavior and an excellent time resolution of <30 ps in the peak and ~50 ps including the tail from recoil electrons. Altogether the new Hamamatsu 2-inch MCP-PMTs show very promising features with still some room for improvements.

An important aspect is the position resolution achievable with the new high granularity MCP-PMT. For this purpose the active surface of the MCP-PMT was illuminated with a highly focused laser spot of <40 μm (FWHM) and scanned along the high resolution coordinate in 50 μm step sizes. The measurements were done outside and inside a magnetic field of up to 1 T. Only 8 adjacent pixels (with a 0.4 mm pitch) were read out and the counts in each pixel above a threshold of 0.04 photo-electrons (p.e.) were plotted as a function of the position and the B-field. The results in Fig. 2 reveal rather long tails for each pixel which cannot be purely from charge sharing among adjacent pixels. Very similar tails of the same size are observed in

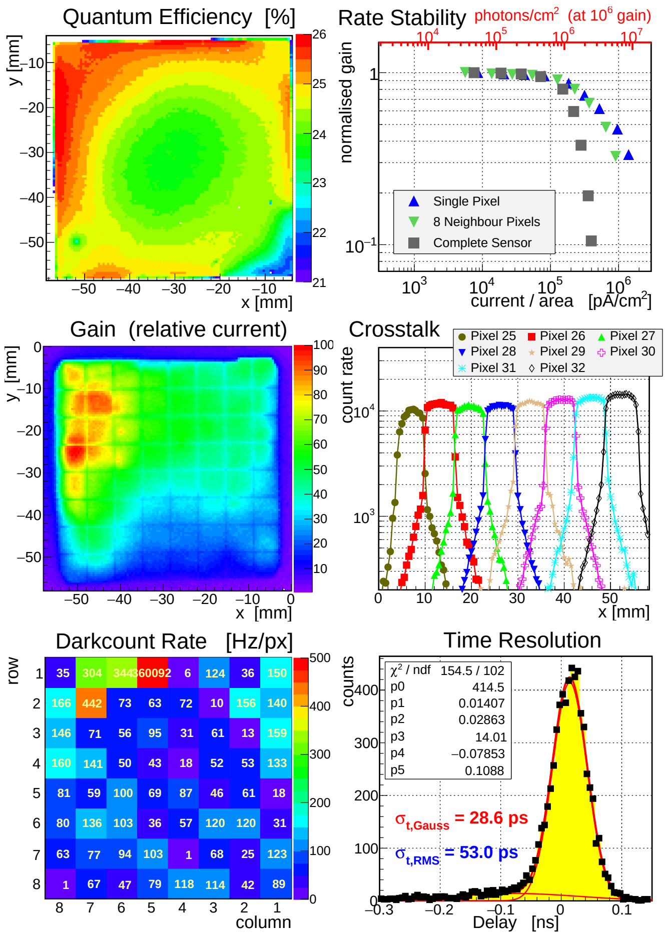

Figure 1: Compilation of the most important properties of the new 2-inch 8×8 pixel Hamamatsu R13266-M64 MCP-PMT JS0035.

the 8×8 pixel version of this MCP-PMT (see also Fig. 1, right center plot). Although the origin of these tails is not understood yet, we assume that there exists some electronic cross talk between pixels. However, this has to be further investigated. As expected, the peaks get narrower with increasing B-field with a resolution of about 0.4 mm (FWHM) at 1 T.

The high granularity of the Hamamatsu R13266-M768 MCP-PMT allows the measurement of the width of the charge cloud at the anode plane as a function of the magnetic field. For this purpose the center of one pixel was illuminated with a laser beam focused to <40 μm diameter and the hits above a threshold of 0.04 p.e. in eight adjacent pixels were counted. From the position distribution of the eight pixels the width of the charge cloud can be determined. We find that the width shrinks from 0.7 mm (FWHM) at 0 T to 0.3 mm (FWHM) at 1 T.

Another possible measurement is the determination of the Lorentz shift in B-fields inside the MCP-PMT. In this case the laser spot is always pointed at the same pixel and eight adjacent pixels are read out. When the PMT axis is tilted versus the direction of the magnetic field at an angle ϕ around an axis perpendicular to the high resolution direction the centroid of the charge cloud shifts along the direction of the high pixelation. By calculating the charge weighted position along the tilt axis

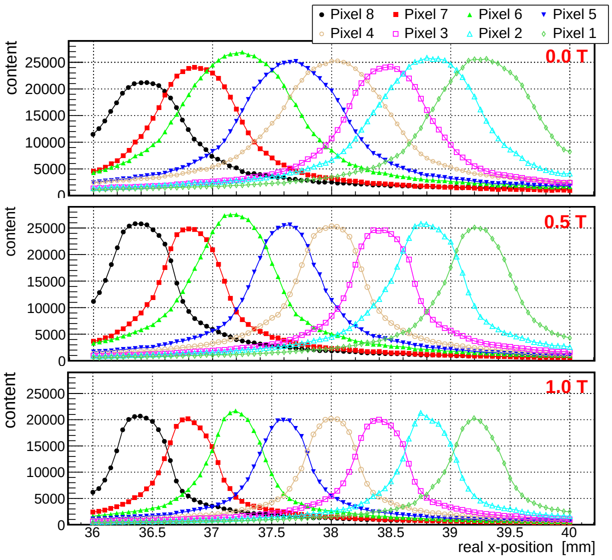

Figure 2: Response of eight adjacent pixels of the new 2-inch 6 × 128 pixel Hamamatsu R13266-M768 MCP-PMT as a function of the photon position outside and inside a magnetic field.

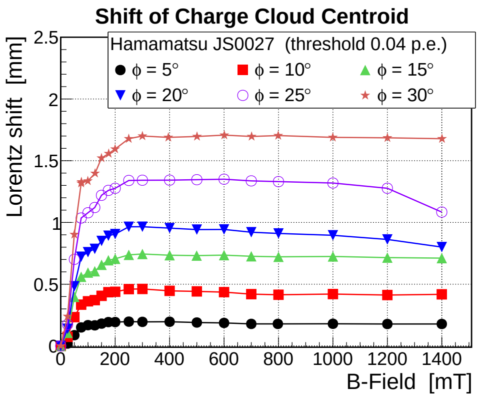

Figure 3: Lorentz shift for different tilt angles ϕ measured inside the new 2-inch 6 × 128 pixel Hamamatsu R13266-M768 MCP-PMT.

one can determine the Lorentz shift which is specific to every MCP-PMT type dependent on the inner structure of the tube. In the case of the Hamamatsu R13266-M768 MCP-PMT we observe a maximum shift of 1.7 mm at $\phi = 30°$, as shown in Fig. 3. This corresponds to 4 pixels and has to be taken into account in a later analysis of experimental data.

3. Lifetime results

In 2011 our group started extensive tests of MCP-PMTs with the goal of measuring the aging behavior of all available lifetime-enhanced MCP-PMTs in the same environment. The tubes are simultaneously illuminated with a common light source at a single photon rate and gain similar to that expected in the PANDA DIRCs. The light is delivered by a 460 nm LED at a rate of 1 MHz, then widened by a diffuser to a large and homogeneous spot at the sensor plane, and finally attenuated to the single photon level by neutral density filters. Currently up to 16 2-inch MCP-PMTs can be included in the setup. The LED light intensity is continuously monitored by a photo diode and the MCP pulse heights of several pixels of each tube are permanently recorded at a highly prescaled rate (10^{-16}) by a VME data acquisition system. The QE within a wavelength band of 250 - 700 nm is measured in steps of $\lambda = 2$ nm with an in-house monochromator [16] powered by a stable xenon lamp. Every few weeks a wavelength scan of the aged MCP-PMTs is done and every few months a complete surface scan of the PC is performed at 372 nm. For technical details of the MCP-PMTs included in the lifetime setup and the lifetime results of non-ALD MCP-PMTs the reader is referred to Ref. [17]. In this paper we will focus on the results of the ALD coated MCP-PMTs.

The QE at 400 nm as a function of the IAC is compared in Fig. 4 for six ALD coated MCP-PMTs. The 2 one-inch Hamamatsu MCP-PMTs R10754X show a slow but steady degradation of the QE, with model KT0001 and model KT0002 reaching half of the original QE at ~14 C/cm^2 and ~10 C/cm^2, respectively. Taking into account the massive QE drop at ~0.6 C/cm^2, which was caused by an HV accident and is not aging related, both KT0001 and KT0002 seem to age similarly. The new Hamamatsu two-inch prototype MCP-PMT R13266 starts loosing QE significantly already at ~1 C/cm^2. This tube has an ALD coating and a film placed in front of the first MCP. The slope of the degradation looks similar to that of one-inch Hamamatsu MCP-PMTs with a film but still without ALD coating [17]. This may indicate that the ALD layer of the R13266 is not yet perfect. The two-inch PHOTONIS XP85112 MCP-PMTs behave somewhat differently. The 9001223 and the 9001332 from the same production batch are equipped with one ALD layer and no film. They show a constant QE up to ~6 C/cm^2 and ~10 C/cm^2, respectively, before a steady degradation starts. At ~8 C/cm^2 the 9001223 has lost half of its original QE, while the QE of the 9001332 will probably reach its half value at ~15 C/cm^2. The model 9001393 is equipped with two ALD layers (one resistive and one secondary electron emissive) and shows absolutely no sign of aging up to 10 C/cm^2. In summary, all ALD coated MCP-PMTs show a lifetime of >5 C/cm^2 which is sufficient for the BD.

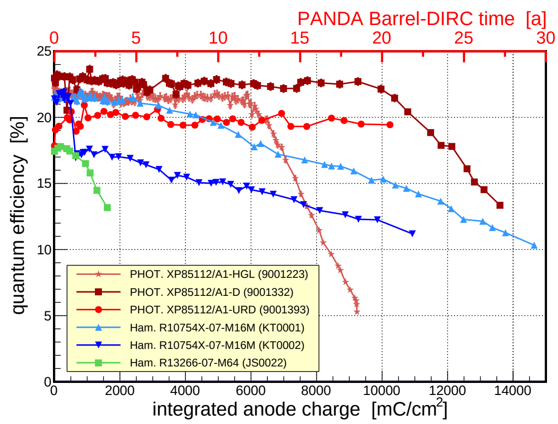

Figure 4: Comparison of the results of our lifetime measurements for different ALD coated MCP-PMTs: QE as a function of the IAC at 400 nm.

As shown in the plots of Fig. 5, also the investigated aging parameters gain, dark count rate (DCR), QE as a function of the wavelength, and surface scans show no sign of aging for the very well performing PHOTONIS XP85112 9001393. At 10 C/cm^2 there is still no PC region where the QE starts to degrade as illustrated in the right column of Fig. 5. Also the other parameters (left column), especially the relative QE show no significant change as the IAC increases. This was different in most other ALD coated MCP-PMTs where the QE started degrading in certain PC regions and a wavelength dependence of the QE drop was observed [17, 18, 19] well below 10 C/cm^2.

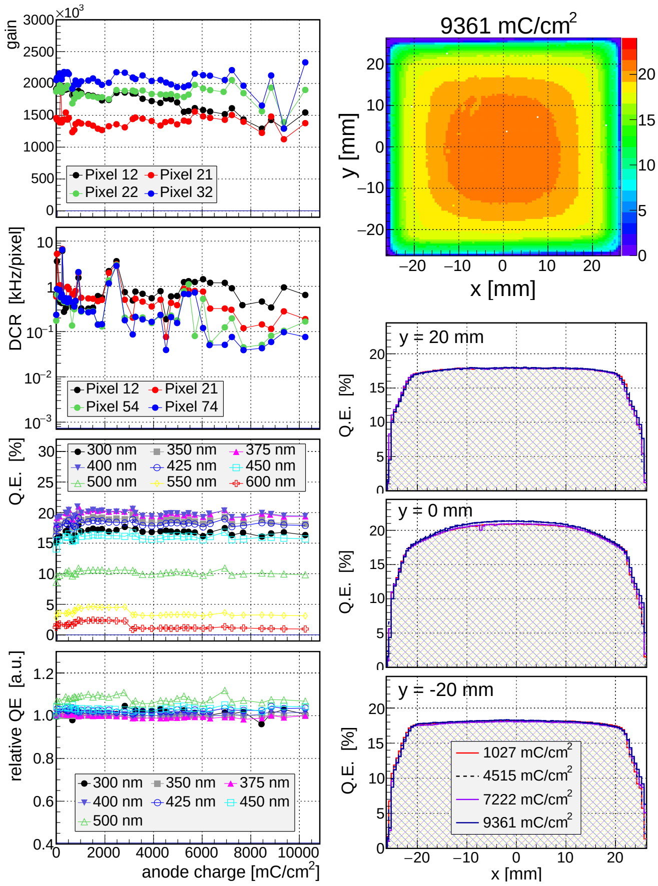

Figure 5: PHOTONIS MCP-PMT XP85112 (9001393); left column: gain, dark count rate (DCR), absolute QE for different wavelength, and relative QE normalized to 350 nm as a function of the IAC; right column: xy-scan of the QE of the PC surface at 9.36 C/cm^2 and QE projections at three y-positions at 4 different IACs.

4. Aging mechanisms

Only one side of the PHOTONIS MCP-PMT 9001223 was illuminated during our campaign which led to a PC surface with an aged and an unaged half. In the results of the position dependent QE scans the illuminated side shows a clear degradation, while the masked side is totally unaffected [18]. This makes this particular MCP-PMT a unique tube for further investigations of the mechanisms involved in the aging process. Because of the pronounced boundary between the two PC halves it is fair to conclude that ion feedback is the dominant cause of MCP aging. Electron stimulated desorption released ions from the MCP surfaces during the charge amplification process, and these ions are accelerated in the direction of the PC where they can impact with kinetic energies ~ keV and degrade the PC performance. In a three-step photo-emission model the damage may occur in any of the processes related to photon absorption, diffusion of the photo electron through the PC material, and escape of the photoelectron at the vacuum surface. To date it has been unclear how the ion feedback impacts these particular processes leading to photoemission.

This aged MCP-PMT was investigated non-destructively at PHOTONIS [20] using spectroscopic ellipsometry (SE), by analyzing photoelectron energies using a retarding potential analysis (RPA) technique, and QE measurements and analysis among the aged and unaged regions of the PC. The SE measurements showed no distinguishable difference in PC optical constants or thickness between the regions indicating that the bulk crystal structure and chemistry of the PC are unaffected by the ion bombardment, and thus the photon absorption is unchanged during the aging. Since the observed wavelength dependence of the QE changes showed larger decreases at long wavelengths, a change in electron affinity (EA) was investigated. Since the two halves were determined to have the same bandgap based on the SE results, comparing the RPA data indicates if there are differences in EA that impact the photoemission. In the case of this half-aged MCP-PMT 9001223, very similar energy distributions and only a small EA increase of 0.13 eV were observed for the aged PC half. While this small EA increase impacts the spectral region beyond 600 nm, calculations show that this small change cannot explain the observed wavelength dependence of the QE ratio across the spectrum, where there are still large QE changes for even the most energetic photoelectrons. Therefore, this EA increase which corresponds to a small change in the work function is certainly not the sole reason for the QE degradation. From high resolution RPA measurements at long wavelengths it was also possible to conclude that PC material was sputtered from the PC onto the input surface of the MCP on the aged half. A mechanism by which this explains the energy dependence of the QE degradation however remains elusive, and in summary it is still unclear how the ion feedback degrades the photoemission process. Further work identifying the particular bombarding ion species by using TOF analysis of the ion-feedback generated afterpulses is ongoing.

5. Conclusions

Our long-term measurements with ALD coated MCP-PMTs from PHOTONIS and Hamamatsu show a lifetime improvement of a factor >50 compared to former MCP-PMTs for most of the tubes. This, however, is not yet the case for the most recent 2-inch prototype MCP-PMT R13266 from Hamamatsu which shows good performance characteristics except that the PC aging starts already at only ~1 C/cm^2. A recent PHOTONIS XP85112 MCP-PMT with two ALD layers shows absolutely no sign of aging up to an IAC of 10 C/cm^2. This could be another significant lifetime improvement compared to the first ALD coated PHOTONIS MCP-PMTs. One of these first tubes (model 9001223 with an aged and an unaged PC half) was shipped to PHOTONIS for a non-destructive investigation of the PC. The first results of their measurements indicate that simple work function arguments are not sufficient to explain the aging mechanisms. Further studies, probably also with other MCP-PMTs, will be necessary to clarify the processes which cause the QE degradation of the PC.

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