Recent results with lifetime enhanced Microchannel-Plate Photomultipliers

M. Pfaffinger[a,*], M. Böhm[a], A. Britting[a], W. Eyrich[a], A. Lehmann[a], F. Uhlig[a], A. Belias[b], R. Dzhygadlo[b], A. Gerhardt[b], K. Gtzen[b], M. Krebs[b], D. Lehmann[b], F. Nerling[b], M. Patsyuk[b], K. Peters[b], G. Schepers[b], L. Schmitt[b], C. Schwarz[b], J. Schwiening[b], M. Traxler[b], M. Zhlsdorf[b], M. Dren[c], E. Etzelmller[c], K. Fhl[c], A. Hayrapetyan[c], B. Krck[c], O. Merle[c], J. Rieke[c], M. Schmidt[c], T. Wasem[c], E. Cowie[d], T. Keri[d], P. Achenbach[e], M. Cardinali[e], M. Hoek[e], W. Lauth[e], S. Schlimme[e], C. Sfienti[e], M. Thiel[e]

[a] *Friedrich Alexander-University of Erlangen-Nuremberg, Erlangen, Germany*
[b] *GSI Helmholtzzentrum fr Schwerionenforschung GmbH, Darmstadt, Germany*
[c] *II. Physikalisches Institut, Justus Liebig-University of Giessen, Giessen, Germany*
[d] *University of Glasgow, Glasgow, United Kingdom*
[e] *Institut fr Kernphysik, Johannes Gutenberg-University of Mainz, Mainz, Germany*

Abstract

The favored photon sensors for the DIRC (detection of internally reflected Cherenkov light) detectors at the $\bar{\text{P}}$ANDA (Anti-proton Annihilation at Darmstadt) experiment at FAIR (Facility for anti-proton and ion research) are micro-channel-plate photomultipliers (MCP-PMTs). The main problem until a few years ago was the limited lifetime of the MCP-PMTs caused by a rapid decrease in quantum efficiency (QE) of the photo cathode (PC) with increasing integrated anode charge (IAC). These limitations are overcome by applying an atomic layer deposition (ALD) coating on the MCPs, as recently done by PHOTONIS and Hamamatsu. During the last years tests of lifetime enhanced MCP-PMTs were performed and their results were compared. For this the QE was measured in dependence of the IAC as function of the wavelength and position dependent across the PC. The best performing tubes show a lifetime increase compared to not enhanced devices by a factor > 50 with an IAC $> 13\,\mathrm{C/cm^2}$. Additionally, performance results of new 2 inch Hamamatsu tubes and a new high QE PHOTONIS tube are presented.

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

1. Introduction

For the $\bar{\text{P}}$ANDA experiment [1, 2] multi anode micro-channel plate photomultipliers (MCP-PMTs) were identified as the only suitable photon sensors for the DIRC detectors [3, 4, 5]. The MCP-PMTs can detect single photons in magnetic fields of > 1 T with a time resolution better than 50 ps. They also show a low dark count rate of $< 1\,\mathrm{kHz/cm^2}$ while being compact enough to fit into the detector. Furthermore, they are able to detect photons at the high rates as they will appear in the $\bar{\text{P}}$anda DIRCs, for the Barrel DIRC (BD) it will be $\sim 200\,\mathrm{kHz/cm^2}$ and up to $1\,\mathrm{MHz/cm^2}$ at the End-cap Disc DIRC (EDD). Assuming these rates over the runtime of the $\bar{\text{P}}$ANDA experiment one can calculate an expected integrated anode charge (IAC) of $\sim 5\,\mathrm{C/cm^2}$ for the BD and even more for the EDD This charge assumes a 10^6 gain of the MCP-PMTs and a runtime of 10 years with a 50% duty cycle. Just a few years ago, this IAC was far beyond the capability of commercially produced MCP-PMTs since the quantum efficiency (QE) usually had dropped by $> 50\%$ at an IAC of just $< 200\,\mathrm{mC/cm^2}$ [6, 7, 8]. This aging of the photo cathode (PC) is probably caused by heavy feedback ions from the residual gas.

In the last years, several approaches to increase the lifetime of MCP-PMTs were made. These include: more robust photo cathodes, improved vacuum, electron scrubbing of MCP surfaces, thin Al_2O_3 films in front of or between the MCP layers [9, 10]. With all these techniques, a clear increase of the lifetime could be obtained, though the breakthrough in lifetime enhancement came with the application of an atomic layer deposition (ALD) on the MCP surfaces. In this process the MCP is coated with a thin layer of alumina or MgO. The first coated MCPs were manufactured by Arradiance Inc. [11] and then taken over by PHOTO-

*Corresponding author
Email address: markus.pfaffinger@fau.de (M. Pfaffinger)

NIS and the LAPPD collaboration [12, 13], Hamamatsu and Photek [14] are also using this approach to increase the lifetime of their MCP-PMTs. The MCPs are covered with up to three different layers: a resistive, a secondary electron emmissive and an electrode layer. With these coatings, the secondary electron yield (SEY) can be tuned and a higher gain at the same voltage compared to not ALD coated devices can be achieved. This paper will only discuss the performance of ALD coated devices. For more information on former results we refer to Refs. [8, 15, 16, 17, 18, 19]

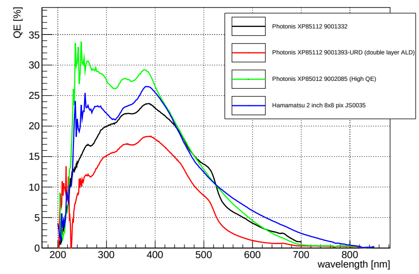
2. Properties of new 2 inch devices

We compare here recent 8x8 pixel sensors from PHOTONIS and Hamamatsu. The PHOTONIS sensor has a high-QE cathode and 25 μm pores without ALD coating. The Hamamatsu tube has 10 μm pores with an ALD coating and an additional protective Al_2O_3 film layer in front of the first MCP. Compared to older PHOTONIS models (see Fig. 1a red & black lines) the Hamamatsu sensor (blue line) showed a better QE especially in the region below 300 nm. The new high-QE PHOTONIS (green line) shows an overall higher QE than the Hamamatsu tube.

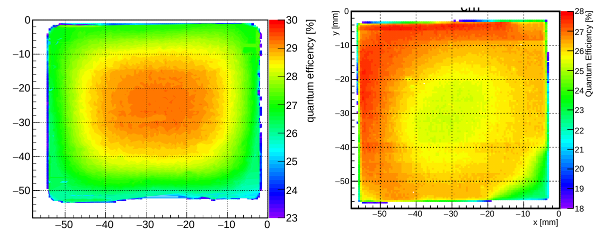
When looking at the position dependent QE scans in Fig. 1a one can see that the PHOTONIS MCP-PMT has a higher QE towards the middle of the sensor. Overall the QE distribution is homogeneous to about 2 % absolute QE. Looking at the Hamamatsu MCP-PMT one can see a very high QE in the top left corner and a QE drop in the bottom right corner. This makes the QE homogeneity of the sensor a bit worse with about 5 % absolute QE difference. The QE scans were made with a PiLas laser system with 372 nm and a stepper unit. The sensors were scanned in 0.5 mm steps. The plots in Fig. 1a and Fig. 1b show gain scans. These scans were made measuring the shortened anode current while scanning the sensors over their surface. It should be taken into account that these scans would folded with the QE of the sensors, thus the obtained scan was divided by the QE scan to get the actual gain homogeneity.

Fig. 1a shows the time resolution of both sensors. This resolution is obtained by measuring the charge and jitter of the signal with a scope and applying a time-walk correction on the data. One can see that the Hamamatsu MCP-PMT has a peak resolution of $\sigma = 27$ ps ($\sigma_{\text{RMS}} = 94$ ps) while the PHOTONIS MCP-PMT has $\sigma = 39$ ps ($\sigma_{\text{RMS}} = 160$ ps). Both sensors are fitting the requested 50 ps for $\bar{\text{P}}$ANDA. However, the comparison is not completely fair. The smaller pores of the Hamamatsu MCP-PMT lead to a better time resolution, thus we would need another PHOTONIS tube with the same pore size as the Hamamatsu to compare the sensors fairly.

As one can see in Fig. 1a the newer models (yellow and green curves) have a worse rate stability than older sensors (blue and magenta curves). This could lead to problems in the later experimental setup and must be fixed. The rate stability can be adjusted by modifying the resistance and capacity of the MCP coating inside the MCP-PMT. Further investigation on the cause of the rate stability drop has to be done.



(a) Comparison of wavelength dependend QE

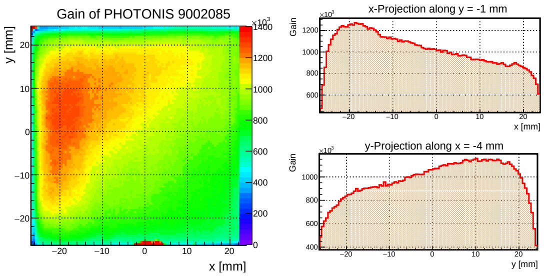


(a) QE scans of PHOTONIS (left) and Hamamatsu (right) MCP-PMT

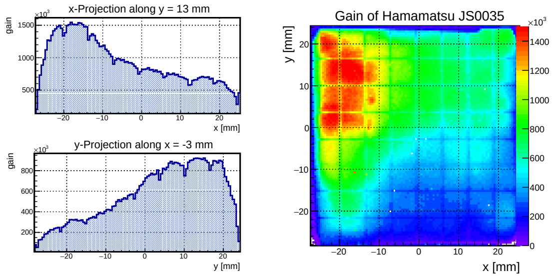
Both sensors look very promising and can be used as sensors for the $\bar{\text{P}}$ANDA DIRC detectors with just a few additional adjustments.

3. Results of latest lifetime measurements

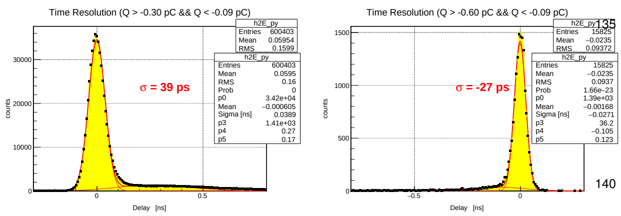
In 2011 the Erlangen group started testing MCP-PMTs with the goal to measure the aging behavior of all available lifetime enhanced MCP-PMTs. The sensors are all illuminated by a common LED with 460 nm wavelength at a photon rate and gain similar to to that expected with the $\bar{\text{P}}$ANDA DIRCs. The LED is pulsed at a rate of 1 MHz and then widened by a diffuser that gives a large homogeneous light spot at the detector plane (about $300 \times 300\,\text{mm}^2$) which allows us to age up to 16 2 inch MCP-PMTs at once. The light is then reduced to single photon level by neutral density filters in front of the sensors. The stability of the light source is



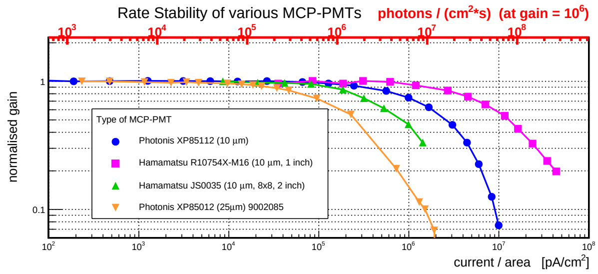
(a) Gain scans of PHOTONIS MCP-PMT



(b) Gain scans of and Hamamatsu MCP-PMT



(a) Time resolution of PHOTONIS (left) and Hamamatsu (right)



(a) Rate stability of different MCP-PMT devices

Figure 1: Comparison of different parameters

monitored by a photo-diode and several pixels of each tube are permanently monitored at a highly pre-scaled rate (2^{-16}) by a VME data acquisition system. With an in-house monochromator [20] powered by a stable xenon arc lamp every few weeks a wavelength scan of all sensors is done in steps of $\lambda = 2$ nm over a range of 250 – 700 nm. Every few months complete surface scans of the PC are done in 0.5 mm steps with a blue laser ($\lambda = 372$ nm). For further information on the sensors included in the setup and the performance of non ALD coated devices the reader is referred to Ref. [21]. This paper will only focus on ALD coated MCPs.

In Fig. 2 the QE at 400 nm as a function of the IAC is compared for different MCP-PMTs. It can be seen that the two 1 inch tubes from Hamamatsu (R10754X) show a steady decrease of the QE from the beginning. The two models KT0001 and KT0002 are reaching half of their original QE at $\sim$14 C/cm^2 and $\sim$10 C/cm^2. Taking into account that the KT0002 shows a massive drop at about $\sim$0.6 C/cm^2, which was caused by an HV accident and is not related to aging caused by accumulated IAC, both sensors behave similar when looking at the aging process. The new 2 inch prototypes (R13266) from Hamamatsu behave very different, while the older models JS0018 and JS0022 went down to half their original QE at $\sim$0.7 C/cm^2 and $\sim$2.8 C/cm^2 the newer models JS0027 and JS0035 show no signs of aging at $\sim$1.2 C/cm^2 and $\sim$2.2 C/cm^2. The slope of the QE vs IAC data of the older models looks similar to to older Hamamatsu models which were equipped with a protection film only and without ALD coating [21]. This indicates maybe a problem with the ALD coating in early devices that seems to be fixed in later produced prototypes.

The behavior of the 2 inch PHOTONIS XP85112 tubes is quite different. The 9001223 and 9001332 are from the same production batch and equipped with one ALD layer and no film. The PC shows no decrease in QE up to about $\sim$6 C/cm^2 and $\sim$10 C/cm^2. The 9001223 reaches about half of its original QE at $\sim$8 C/cm^2 while the 9001332 reaches this point at about $\sim$14.3 C/cm^2. The model 9001393 has two ALD layers: a resistive and a secondary electron emissive. This model shows no signs of aging till $\sim$14 C/cm^2 (the latest value measured). Looking at the measured data we can say that all ALD coated devices should reach the requested lifetime of > 5 C/cm^2 for the BD.

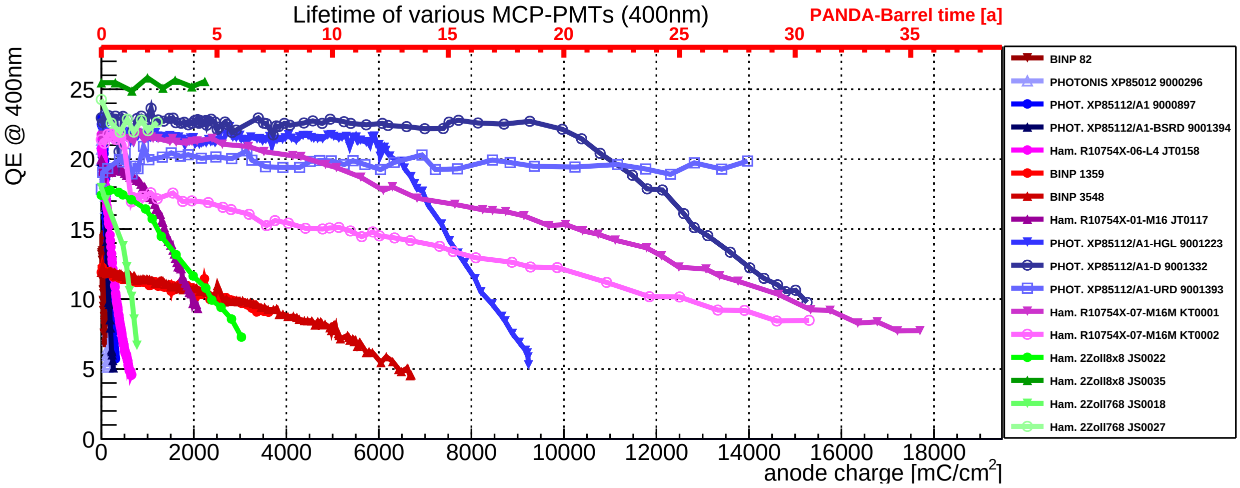
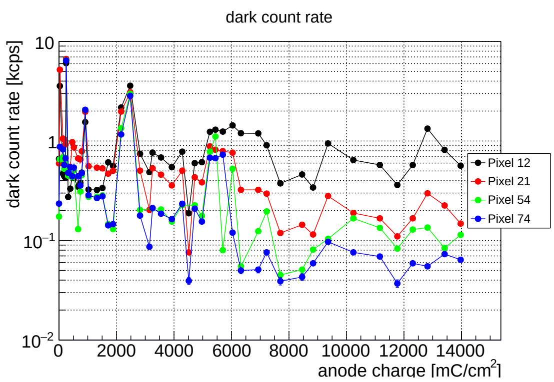
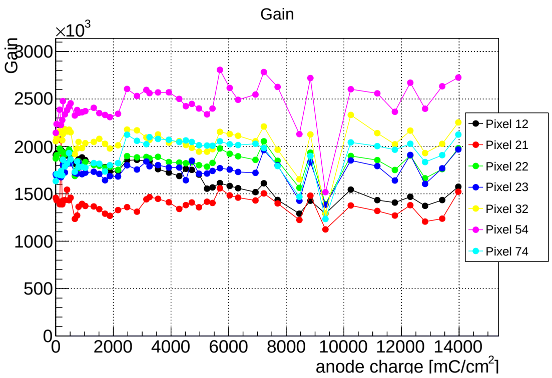


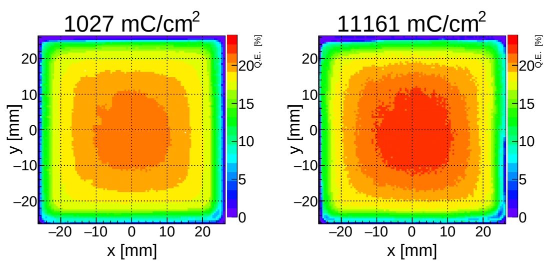
Figure 2: Comparison of our lifetime measurement results



(a) Darkcount rate vs IAC of 9001393



(b) Gain vs IAC of 9001393



(c) QE Scan of 9001393

Figure 3: Different Parameters of tube 9001393

As shown in Fig. 3 for the excellent performing PHOTONIS XP85112 9001393 the aging parameters dark-count rate (DCR), gain, QE as function of the wavelength and the PC surface show no sign of aging. All other devices showed a QE drop in a certain region on the PC and a wavelength dependent drop of the QE well below $\sim 14\,\mathrm{C/cm^2}$ [21, 22, 23].

4. Conclusions

The long-term measurements of ALD coated devices from Hamamatsu and PHOTONIS show a significant increase in lifetime of a factor > 50 compared to former not lifetime enhanced MCP-PMTs. However, the first produced models of the Hamamatsu 2x2 inch^2 prototype MCP-PMT R13266 start PC aging effects already at or below $\sim 1\,\mathrm{C/cm^2}$. This problem seems to be solved in later produced models (JS0035) which show no aging yet. The PHOTONIS tube with double ALD coating (9001393) shows no signs of cathode damage at an IAC of $\sim 14\,\mathrm{C/cm^2}$. This is another significant improvement of the lifetime compared to the first ALD coated devices from PHOTONIS.

Acknowledgments

We thank our Erlangen colleagues of ECAP for granting us use of the QE setup. This work is supported by the German BMBF and GSI Darmstadt.

References

[1] PANDA Collaboration, Technical progress report, FAIR-ESAC/Pbar 2005.

[2] PANDA Collaboration, Physics performance report 2009. arXiv:0903.3905v1.

[3] P. Coyle, et al., The dirc counter: a new type of particle identification device for b factories, Nucl. Instr. and Meth. A 343 (1) (1994) 292 – 299. doi:10.1016/0168-9002(94)90568-1.

[4] R. Dzhygadlo, et al., High-performance dirc detector for the future electron ion collider experiment, Journal of Instrumentation 11 (07) (2016) C07015.
URL http://stacks.iop.org/1748-0221/11/i=07/a=C07015

[5] M. Düren, et al., The endcap disc dirc of panda, Nucl. Instr. and Meth. A. doi:10.1016/j.nima.2017.02.077.

[6] N. Kishimoto, et al., Lifetime of MCP-PMT, Nucl. Instrum. Meth. A 564 (2006) 204–211. doi:10.1016/j.nima.2006.04.089.

[7] A. Britting, et al., Lifetime-issues of MCP-PMTs, JINST 6 (2011) C10001. doi:10.1088/1748-0221/6/10/C10001.

[8] F. Uhlig, et al., Performance studies of microchannel plate PMTs, Nucl. Instrum. Meth. A 695 (2012) 68–70. doi:10.1016/j.nima.2011.12.062.

[9] T. Jinno, et al., Lifetime-Extended MCP-PMT, Nucl. Instrum. Meth. A 629 (2011) 111–117. arXiv:1010.1057, doi:10.1016/j.nima.2010.10.145.

[10] M. Y. Barnyakov, A. V. Mironov, Photocathode aging in mcp pmt, Journal of Instrumentation 6 (12) (2011) C12026.
URL http://stacks.iop.org/1748-0221/6/i=12/a=C12026

[11] D. Beaulieu, et al., Nano-engineered ultra-high-gain microchannel plates, Nucl. Instr. and Meth. A 607 (1) (2009) 81 – 84, radiation Imaging Detectors 2008. doi:10.1016/j.nima.2009.03.134.

[12] M. Wetstein, et al., Development of sub-nanosecond, high gain structures for time-of-flight ring imaging in large area detectors, Nucl. Instr. and Meth. A 639 (1) (2011) 148 – 150. doi:10.1016/j.nima.2010.10.084.

[13] O. Siegmund, et al., Atomic layer deposited borosilicate glass microchannel plates for large area event counting detectors, Nucl. Instr. and Meth. A 695 (2012) 168 – 171, new Developments in Photodetection NDIP11. doi:10.1016/j.nima.2011.11.022.

[14] T. M. Conneely, et al., Extended lifetime mcp-pmts: Characterisation and lifetime measurements of ald coated microchannel plates, in a sealed photomultiplier tube, Nucl. Instr. and Meth. A 732 (2013) 388 – 391, vienna Conference on Instrumentation 2013. doi:10.1016/j.nima.2013.07.023.

[15] A. Lehmann, et al., Performance studies of microchannel plate pmts in high magnetic fields, Nucl. Instr. and Meth. A 595 (1) (2008) 173 – 176, rICH 2007. doi:10.1016/j.nima.2008.07.083.

[16] A. Lehmann, et al., Studies of mcp properties, Journal of Instrumentation 4 (11) (2009) P11024.
URL http://stacks.iop.org/1748-0221/4/i=11/a=P11024

[17] A. Lehmann, et al., Systematic studies of micro-channel plate pmts, Nucl. Instr. and Meth. A 639 (1) (2011) 144 – 147. doi:10.1016/j.nima.2010.09.071.

[18] A. Lehmann, et al., Lifetime of mcp-pmts, Journal of Instrumentation 9 (02) (2014) C02009.
URL http://stacks.iop.org/1748-0221/9/i=02/a=C02009

[19] A. Lehmann, et al., Recent developments with microchannel-plate pmts, Nucl. Instr. and Meth. A. doi:10.1016/j.nima.2016.12.063.

[20] B. Herold, O. Kalekin, Pmt characterisation for the km3net project, Nucl. Instr. and Meth. A 626 (2011) S151 – S153. doi:10.1016/j.nima.2010.04.129.

[21] A. Lehmann, et al., Tremendously increased lifetime of mcp-pmts, Nucl. Instr. and Meth. A 845 (2017) 570 – 574. doi:10.1016/j.nima.2016.05.017.

[22] A. Lehmann, et al., Lifetime of mcp-pmts, Journal of Instrumentation 11 (05) (2016) C05009.
URL http://stacks.iop.org/1748-0221/11/i=05/a=C05009

[23] F. Uhlig, et al., Breakthrough in the lifetime of microchannel plate photomultipliers, Nucl. Instr. and Meth. A 787 (2015) 105 – 109. doi:10.1016/j.nima.2014.11.046.