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# Lifetime of MCP-PMTs

**A. Lehmann,[a,1] A. Britting,[a] W. Eyrich,[a] M. Pfaffinger,[a] F. Uhlig,[a] A. Belias,[b] R. Dzhygadlo,[b] A. Gerhardt,[b] K. Götzen,[b] G. Kalicy,[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. Zühlsdorf,[b] M. Düren,[c] E. Etzelmüller,[c] K. Föhl,[c] A. Hayrapetyan,[c] B. Kröck,[c] O. Merle,[c] J. Rieke,[c] M. Schmidt,[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 für Schwerionenforschung GmbH, Darmstadt, Germany*
[c] *II. Physikalisches Institut, Justus Liebig-University of Giessen, Giessen, Germany*
[d] *University of Glasgow, Glasgow, United Kingdom*
[e] *Institut für Kernphysik, Johannes Gutenberg-University of Mainz, Mainz, Germany*

*E-mail:* `Albert.Lehmann@physik.uni-erlangen.de`

Abstract: The hadron identification in the PANDA experiment at FAIR will be done with DIRC detectors. Because of design and space reasons the sensors of the DIRCs have to be placed inside the strong magnetic field of the solenoid. As the favored photon sensors microchannel-plate photomultipliers (MCP-PMTs) were identified. However, these devices showed serious aging problems until very recently, which manifest themselves by a fast degrading quantum efficiency (QE) of the photo cathode (PC). This is mainly due to feedback ions from the residual gas. In this paper we discuss the recently accomplished huge improvements in the lifetime of MCP-PMTs. With innovative countermeasures applied to the MCP-PMTs in the attempt to reduce the aging effects the manufacturers were able to increase the lifetime of MCP-PMT prototypes by almost two orders of magnitude compared to the former commercially available devices. Our group has studied the aging of MCP-PMTs for more than four years by simultaneously illuminating different types of lifetime-enhanced MCP-PMTs at the same photon rate. Gain, dark count rate, and QE as a function of the wavelength and the PC surface were measured in regular time intervals and studied in dependence of the integrated anode charge. We observe that MCP-PMTs treated with an atomic layer deposition (ALD) technique are by far the best devices available now. A lifetime of up to 10 C/cm$^2$ integrated anode charge was reached with these sensors. This is sufficient for both PANDA DIRCs.

Keywords: Photon detectors for UV, visible and IR photons (vacuum), Microchannel-plate photomultipliers, Cherenkov detectors.

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[1] Corresponding author.

## Contents

## 1 Introduction

PANDA [1] is one of the four pillar experiments at the new FAIR accelerator complex at GSI in Darmstadt, Germany. Cooled antiproton beams up to 15 GeV/c will be available in a high energy storage ring (HESR) to address fundamental questions in hadron and particle physics [2]. An important component of the PANDA detector will be a subdetector system for hadron identification, in particular for the separation of pions and kaons up to 4 GeV/c. Because of spacial boundary conditions these two Cherenkov detectors will be of the DIRC (Detection of Internally Reflected Cherenkov light) type [3], with a "Barrel DIRC" (BD) cylindrically surrounding the interaction region and an "Endcap Disc DIRC" (EDD) in the forward hemisphere. Details about the PANDA DIRC detectors are given in Refs. [4–6].

The image planes of both DIRCs will be located inside the magnetic field of a 2 Tesla solenoid. This requires photon sensors with enough gain for an efficient single photon detection inside these strong fields. Since the readout plane is very compact and to reconstruct the Cherenkov angle of each photon with sufficient resolution a good to excellent position resolution of about 5x5 mm$^2$/pixel for the BD and 0.5x16 mm$^2$/pixel for the EDD is needed. To enable a moderate correction of chromatic dispersion effects in the radiators and to suppress background events the photon time-of-propagation (ToP) has to be measured with a time resolution of <100 ps. The average antiproton-proton annihilation rate in PANDA will be up to 20 MHz. Simulations show that this will lead to photon densities of ~200 kHz/cm$^2$ at the BD and of ~1 MHz/cm$^2$ at the EDD image planes. Most likely wavelength filters will be placed in front of the sensors of the EDD to reduce the photon rate to about that expected for the BD.

Microchannel plate (MCP) photo multipliers (PMTs) are the ideal sensors for fast single photon detection inside magnetic fields. They are compact with a good active area ratio and can be produced as multi-anode devices with various anode pixel matrices. However, until recently the main drawback of MCP-PMTs have been serious aging issues which lead to a rapidly decreasing quantum efficiency (QE) of the photo cathode (PC) while the integral anode charge accumulates. Taking into account the photon rates given above and assuming 50% duty cycle of PANDA at a sensor gain of $10^6$ we expect an integrated anode charge of about 5 C/cm$^2$ at the BD over a period of 10 years. Until very recently these limits were far beyond the reach of any commercially available MCP-PMT. In the older devices the QE had dropped to less than half of its original value after less than 200 mC/cm$^2$ [7, 8].

## 2 Approaches to increase the lifetime

Until very recently their limited lifetime was the major reason against a more frequent application of MCP-PMTs for photon detection despite their otherwise advantageous properties. However, the need for compact and fast Cherenkov detectors [4, 9, 10] for particle identification, placed inside strong magnetic fields and facing a high rate environment, has revived the interest in MCP-PMTs during the last several years. This led to new strategies in tackling the aging issue.

### 2.1 Possible causes of MCP aging

Although the aging process of MCP-PMTs is not yet fully understood there are strong arguments about the most likely causes. During the amplification process some atoms like e.g. hydrogen and lead may be desorbed from the MCP material, which could damage the MCP surfaces and affect the gain. Those and other residual gas atoms may be ionized in the electron avalanche and will be accelerated towards the PC. Both the impact of in particular the heavy ions and possible reactions of these and other ions at the PC surface may damage the structure of the PC and the work function could change gradually. This leads to a degradation of the QE. Another cause of MCP aging may be neutral molecules like e.g. $CO_2$, $O_2$ or $H_2O$ [11] which may be existent in small amounts in the residual gas and can also react with the PC.

### 2.2 First approaches to reduce aging

Placing a thin $Al_2O_3$ protection film in front to the first MCP layer was one of the first attempts undertaken by Hamamatsu and the Budker Institute of Nuclear Physics (BINP) in Novosibirsk to effectively stop feedback ions before reaching the PC. The disadvantage of this approach is a reduced collection efficiency of ~30% since the photo electrons from the PC have to first penetrate this film before being multiplied. To avoid this problem in later generation MCP-PMTs (R10754X) Hamamatsu has placed the film between the first and second MCP. Furthermore, the anode region was hermetically sealed from the PC region to prevent neutral molecules of the anode region from reaching the PC [11]. Other manufacturers as PHOTONIS and later also BINP made serious attempts to improve the vacuum quality inside the MCP-PMT and to polish the MCP surfaces by extensive electron scrubbing.

### 2.3 More robust photo cathode

The latest generation BINP MCP-PMTs are without a protection film, but with an improved vacuum and heavily polished MCP surfaces. The major innovation in these tubes is a modified PC to make it more robust against feedback ions. Different types of bialkali photocathodes were manufactured and tested at BINP [12]. The used $Na_2KSb$ substrate was activated in Cs vapors to replace some Na atoms with cesium. Additional treatment in both Cs and Sb vapors increased the dark count rate significantly ($\sim$100 kHz/cm$^2$) but also made the PC much more robust.

### 2.4 Atomic layer deposition (ALD)

A very different approach to enhance the lifetime is taken in the latest PHOTONIS MCP-PMTs (XP85112). To seal the lead glass capillaries of the MCPs and prevent desorption of gaseous contaminants, these are coated with very thin layers of resistive and/or secondary electron emissive materials directly at the pores. This results in a significantly higher gain, a lower secondary electron energy, and finally also a lower probability for ion production [13]. This innovative technique is called atomic layer deposition (ALD) and was first suggested by Arradiance Inc. [14]. Later on it was applied by PHOTONIS and other customers [15, 16], recently also by Hamamatsu and Photek. Currently this technique appears to be the most promising approach to reduce the aging process and to increase the lifetime of MCP-PMTs.

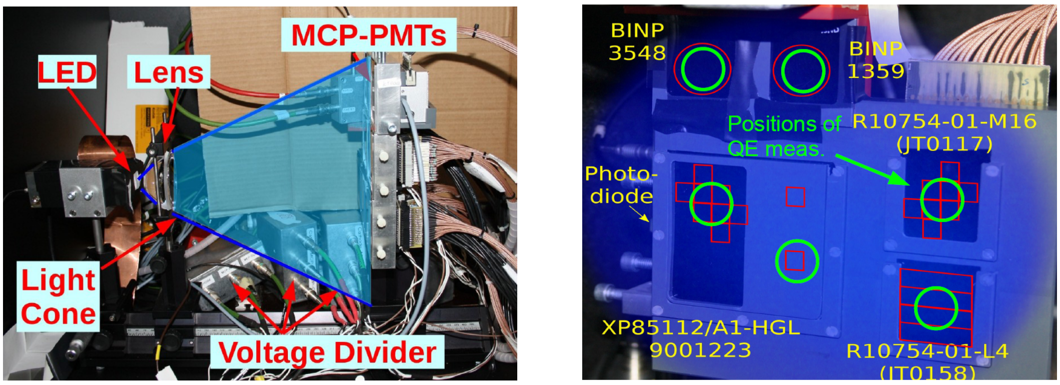
## 3 Results of aging tests

In the last years our group has characterized many different types of MCP-PMTs of the manufacturers PHOTONIS, Hamamatsu and BINP. The setups and methods applied to measure their typical performance properties as well as some of the obtained results are described and discussed in Refs. [17–20]. Recently these investigations were focused on lifetime measurements, first with commercially available standard MCP-PMTs without countermeasures for aging reduction and later in a comparative longterm measurement with several lifetime-enhanced prototype MCP-PMTs of the manufacturers mentioned above.

### 3.1 Measurement setup

A few years ago there existed only very few lifetime data for MCP-PMTs [7, 21]. Moreover, these measurements were done in quite different environments and the results are difficult to compare. Therefore, in the year 2011 our group has started a dedicated aging study with the goal of testing all available types of lifetime-enhanced prototype MCP-PMTs in the same environment and to be able to judge on the best technique against aging.

The tubes were simultaneously illuminated with a common light source at a single photon rate as is expected in the PANDA DIRCs. The light was delivered by a 460 nm LED, then widened by a lens to a large and homogeneous spot at the sensor plane, and finally attenuated to the single photon level by neutral density filters (see figure 1). With a photon rate of 250 kHz at the beginning of the measurements and 1 MHz later to accelerate the aging and a gain of $\sim 10^6$ an integrated charge between 3 and 20 mC/cm$^2$/day was accumulated at the anodes of the MCP-PMTs. The LED light intensity was continuously monitored by a photo diode and the MCP pulse heights of several pixel of each tube were permanently recorded at a highly prescaled rate by a VME data acquisition system. To measure the QE in a wavelength band of 250 - 700 nm there exists an in-house monochromator [22] with $\Delta\lambda$ = 1 nm powered by a stable xenon lamp. Every few days (later weeks) a wavelength scan of the aged MCP-PMTs was done and every few weeks (later months) a complete surface scan of the PC was performed at 372 nm.



(a) side view

(b) view of the sensor plane with blue light spot

**Figure 1**: Illumination setup in an early stage of the aging studies: the red circles and rectangles indicate the pixels permanently read out during the illumination process; the green circles are the positions at the MCP-PMTs where the QE wavelength scan was done.

**Table 1**: Characteristics of the investigated lifetime-enhanced prototype MCP-PMTs. The numbers given in the rows for the integrated anode current (IAC) and latest QE (QE) divided by original QE ($QE_{orig}$) at 400 nm correspond to the different sensor IDs.

| Manufacturer | BINP | PHOTONIS | Hamamatsu | |
|---|---|---|---|---|
| Type | | XP85112 | R10754X-M16 | R10754X-M16M |
| Sensor ID | #1359 / #3548 | 1223 / 1332 / 1393 | JT0117 | KT0001 / KT0002 |
| Pore size ($\mu$m) | 7 | 10 | 10 | |
| Pixels | 1 | 8×8 | 4×4 | |
| $A_{active}$ (mm$^2$) | $9^2\ \pi$ | 53×53 | 22×22 | |
| $A_{total}$ (mm$^2$) | $15.5^2\ \pi$ | 59×59 | 27.5×27.5 | |
| Geom. eff. (%) | 36 | 81 | 61 | |
| IAC (C/cm$^2$) | 3.62 / 6.70 | 9.23 / 9.26 / 5.44 | 2.09 | 10.04 / 5.87 |
| $QE/QE_{orig}$ (%) | 74 / 37 | 24 / 100 / 104 | 47 | 71 / 70 |
| Comments | better vacuum;<br>modified PC | ALD surfaces;<br>1- / 1- / 2-layer | film between<br>$1^{st}$ & $2^{nd}$ MCP | ALD surfaces<br>and film |

The technical characteristics of the MCP-PMTs included in the lifetime setup are listed in table 1. At the beginning of the measurements four standard MCP-PMTs (1x BINP and 2x PHOTONIS; not listed in the table) with no countermeasures against aging were included in the setup. In 2011 the first lifetime-enhanced MCP-PMTs (PHOTONIS 9001223 with ALD coating and 2x BINP with modified PC) were added. Up to now eight lifetime-enhanced MCP-PMTs were included in the setup: 2x BINP with modified PC, 1x Hamamatsu with a protection film and 2x with ALD + film, and 3x PHOTONIS with ALD coating (2 identical tubes with fired lead glass and 1 ALD layer; and 1 tube with unfired lead glass and 2 ALD layers [resistive and secondary electron emissive]). In these large PHOTONIS MCP-PMTs half of the PC surface was covered during the whole illumination process.

### 3.2 Gain and dark count rate

In figure 2 the gain (upper row) and dark count rates (lower row) are plotted as a function of the integrated anode charge. Compared are MCP-PMTs with a modified PC (left), a protection film (middle) and an ALD coating (right). While for the MCP-PMTs with a modified PC (BINP) and with a film (Hamamatsu) the gain changes only moderately, the gain drop for the ALD coated tube (PHOTONIS) can be more than a factor two. However, a modest gain change can easily be compensated by adjusting the high voltage.

An interesting behavior is observed in the dark count rates. For the MCP-PMTs with the modified PC and with a protection film it drops exponentially over several orders of magnitude. This effect may point to a modification of the PC work function. This behavior of the dark count rate is not observed in the ALD coated MCP-PMT at least up to 6 C/cm$^2$.

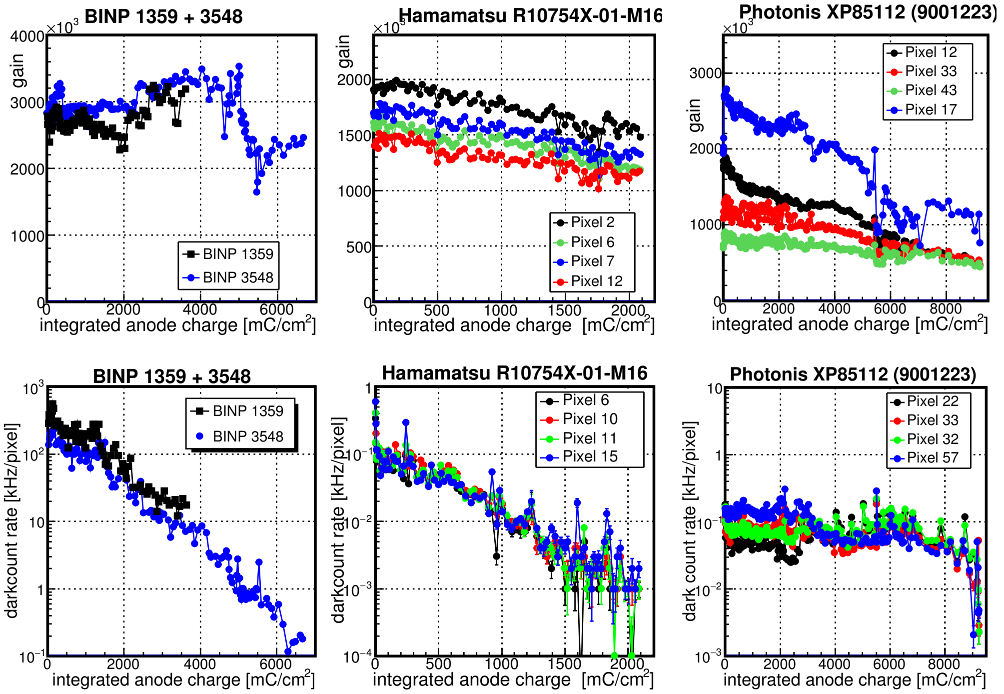


**Figure 2**: Gain [upper] and dark count rate [lower]) as a function of the integrated anode charge. Compared are MCP-PMTs with modified PC (left), film (middle), and ALD coating (right).

### 3.3 Spectral quantum efficiency

In figure 3 the absolute (upper row) and relative QE (lower row) normalized to 350 nm is displayed as a function of the integrated anode charge for different wavelengths. Again compared are MCP-PMTs with a modified PC from BINP (left), a protection film from Hamamatsu (middle) and an ALD coating from PHOTONIS (right). The absolute QE of the BINP MCP-PMT shows a continuous degradation with no obvious trends being visible in the relative QE. The situation is very different for the Hamamatsu tube where the absolute QE is almost stable up to 1 C/cm$^2$ and drops rapidly at higher anode charges. In the relative QE one observes that the QE obviously drops faster for red light than for blue light. This behavior is also visible above 6 C/cm$^2$ in the ALD coated MCP-PMT from PHOTONIS. At this integrated anode charge the absolute QE also starts to decline. The observed QE wavelength dependence is another hint that the PC work function changes when the PC gets damaged.

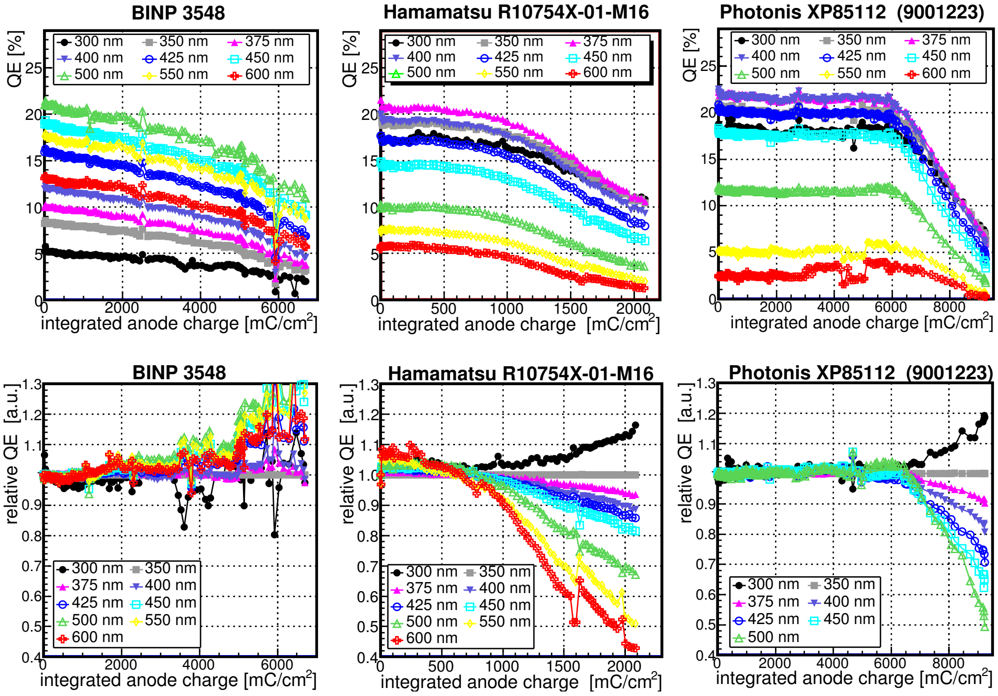


**Figure 3**: Quantum efficiency (absolute [upper] and relative to 350 nm [lower]) as a function of the integrated anode charge for different wavelengths. Compared are MCP-PMTs with modified PC (left), film (middle), and ALD coating (right)

A compilation of the QE dependence at 400 nm as a function of the integrated anode charge is compared in figure 4 for all types of MCP-PMTs whose lifetimes were measured in our setup. The data with the open symbols (very left) show the QE for MCP-PMTs without countermeasures against aging. For all these tubes the QE drops very fast. The MCP-PMT with a protection film shows a significant lifetime improvement but clearly not sufficient for the use in the PANDA DIRCs. In the BINP tubes with a modified PC the QE drops steadily with increasing anode charge until at around 6 C/cm$^2$ the absolute QE has reach 50% of its original value. The real breakthrough in the lifetime is reached with the ALD coated MCP-PMTs: all measured tubes from PHOTONIS and Hamamatsu exceed the PANDA lifetime benchmark of 5 C/cm$^2$ integrated anode charge, some even significantly more. This is a lifetime improvement compared to former MCP-PMTs by a factor >30. These data demonstrate that the ALD coating technique used as countermeasure against the aging of the MCP-PMTs has brought a breakthrough for the application of MCP-PMTs in high rate experiments. Similar results were obtained by MCP-PMT lifetime measurements for the Belle II experiment [11, 23].

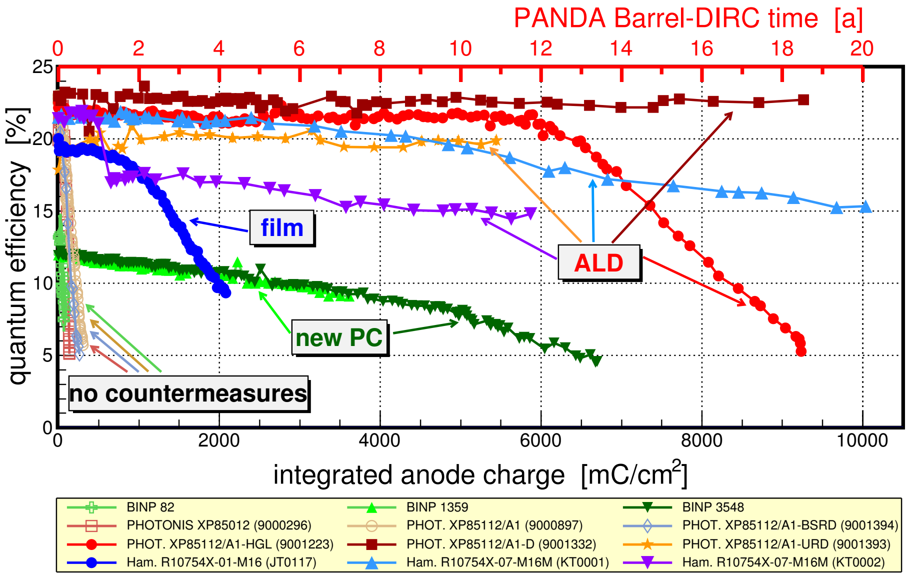


**Figure 4**: Comparison of the results of our lifetime measurements for different MCP-PMTs: quantum efficiency as a function of the integrated anode charge at 400 nm.

### 3.4 Quantum efficient scans

The spectral QE was determined at dedicated PC positions with a light spot size of ~1 cm (see figure 1). In order to study the QE behavior as a function of the position, xy-scans across the PC surface were performed in steps of 0.5 mm. Focused laser light of 372 nm with a narrow spot size of ~0.5 mm was moved across the active PC surface of the MCP-PMT and the photo current was measured. Regularly the photo current was also measured with a calibrated photo diode to calculate the QE. These xy-scans were first done every few weeks and later every few months for all illuminated MCP-PMTs.

In earlier papers [24] we reported that the QE degradation of the BINP MCP-PMTs with a modified PC and that of the Hamamatsu R10754X with a protection film always seems to start at the corners and rims and then it moves towards the center of the PC. In figure 5 the QE surface scans for the two identically designed PHOTONIS XP85112 MCP-PMTs 9001223 and 9001332 with ALD coating are shown for different integrated anode charges. It is important to point out here that only the left half ($x < 0$) of the PC was illuminated while the right half ($x > 0$) was always covered. In the plots for the XP85112 9001223 (upper row) a slight QE degradation at the upper rim is visible at 5.9 C/cm$^2$. With increasing anode charge this QE degradation gets larger and spreads across the whole illuminated PC area, while the QE of the covered side of the PC remains unaffected. For the XP85112 9001332 MCP-PMT (lower row) the QE remains almost constant up to 6.1 C/cm$^2$. Only a slight increase of the QE is observed at the illuminated PC half.

The observation of a QE degradation solely at the illuminated area indicates that the damage to the PC is caused by feedback ions. If neutral molecules were significantly contributing to the aging one should also expect a degrading QE in the covered PC area.

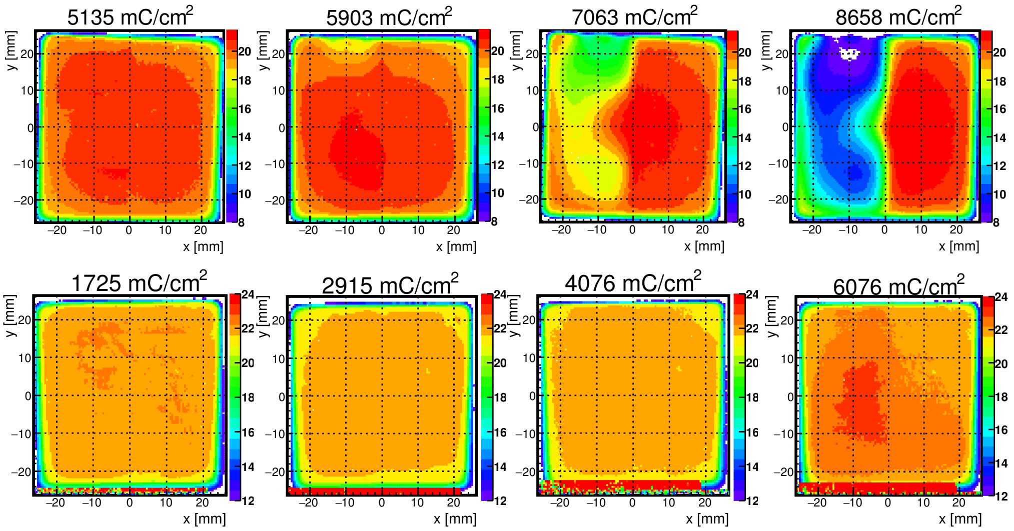


**Figure 5**: QE chart (in % [color level]) at 372 nm for two ALD coated PHOTONIS XP85112 MCP-PMTs (9001223 [upper] and 9001332 [lower]) as a function of the PC surface. The active area of these MCP-PMTs is 53x53 mm$^2$. The right PC half was always covered during the illumination.

## 4 Conclusions

In our extensive aging studies prototypes of lifetime-enhanced MCP-PMTs were illuminated for up to four years at single photon rates as expected in the PANDA DIRCs. The main aging symptom is a QE degradation of the PC with a stronger effect for longer photon wavelengths. This and the exponential decline of the dark count rate indicates that a change of the PC work function is one of the main reasons of MCP-PMT aging. In the surface scans we observe that the QE degradation starts from the rims and corners of the PC and spreads to the center. The comparison of the QE at different integrated anode charges in the illuminated and covered halves of the large PHOTONIS MCP-PMTs suggests that ion feedback is the dominant aging process.

The new lifetime-enhanced MCP-PMTs reveal a spectacular lifetime increase due to recent design improvements. Especially with the innovative ALD technique to coat the MCP surfaces a lifetime increase of a factor >30 was accomplished. This is a huge step forward in the applicability of MCP-PMTs in high rate experiments. In particular, equipping both PANDA DIRCs with the new MCP-PMTs appears feasible now.

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