Tremendously Increased Lifetime of MCP-PMTs

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Abstract

Microchannel plate (MCP) PMTs are very attractive photon sensors for low light level applications in strong magnetic fields. However, until recently the main drawback of MCP-PMTs was their aging behavior which manifests itself in a limited lifetime due to a rapidly decreasing quantum efficiency (QE) of the photo cathode (PC) as the integrated anode charge (IAC) increases. In the latest models of PHOTONIS, Hamamatsu, and BINP novel techniques are applied to avoid these aging effects which are supposed to be mainly caused by feedback ion impinging on the PC and damaging it. Since more than four years we are running a long-term aging test with new lifetime-enhanced MCP-PMT models by simultaneously illuminating various PMTs with roughly the same photon rate. This allows a fair comparison of the lifetime of all investigated MCP-PMTs and will give some insight in the best techniques to be applied for a lifetime enhancement. In this paper the results of comprehensive aging tests will be discussed. Gain, dark count rate and QE were investigated for their dependence on the IAC. The QE was measured spectrally resolved and as a function of the position across the PC to identify regions where the damage develops first. For the best performing tubes the lifetime improvement compared to former MCP-PMTs is a factor of ~50 based on an IAC of meanwhile >10 C/cm^2. This breakthrough in the lifetime of MCP-PMTs was achieved by coating the MCP pores with an atomic layer deposition (ALD) technique.

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

1. Introduction

The hadron identification, in particular the separation of pions and kaons, at the PANDA experiment [1] of the new Facility for Antiproton and Ion Research (FAIR) at GSI, Germany, will be done with DIRC detectors [2]. Due to the compactness of the PANDA detector the image planes of the DIRCs [3, 4, 5] will be placed inside the magnetic field of the solenoid of the target spectrometer. This requires photon sensors immune to an up to 2 Tesla magnetic field. A dense array of anode pixels is needed to allow the reconstruction of the Cherenkov angles with a sufficiently high resolution. The single photon time resolution of the sensors should be σ_t <100 ps to allow the correction of chromatic dispersion effects in the radiator bars and to measure the time-of-propagation of the photons. Moreover, the antiproton-proton average annihilation rate of 20 MHz in the PANDA experiment will lead to densities at the DIRC image planes of 200 - 800 kHz/cm^2 detected photons.

Microchannel-plate (MCP) PMTs are the favored photon sensors. They are commercially available as multi-anode devices and provide a good active area ratio while still being quite compact in size. MCP-PMTs show very promising properties in terms of single photon sensitivity, time resolution, B-field immunity, and dark count rate [6, 7, 8] except that aging was a serious issue. While the integrated anode charge (IAC) increases the photo cathode (PC) gets gradually damaged and the quantum efficiency (QE) starts dropping. Just about 4 years ago the best MCP-PMTs were unusable after <200 mC/cm^2 IAC [7, 9], while for the PANDA DIRCs at least 5 C/cm^2 are needed.

Despite their otherwise advantageous properties the lifetime problem was the main obstacle against a more frequent usage of MCP-PMTs for fast photon detection purposes until very recently. However, the need for compact and fast Cherenkov detectors [5, 10, 11] for particle identification, often 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. Countermeasures against aging

The cause of MCP aging is not yet fully understood in detail but a few scenarios are discussed. During the electron amplification process atoms, in particular hydrogen and lead, may be

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Table 1: Characteristics of the investigated lifetime-enhanced prototype MCP-PMTs (status March 7, 2016). 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	R13266-07-M64
Sensor ID	#1359 / #3548	1223 / 1332 / 1393	JT0117	KT0001 / KT0002	JS0022
Pore size (μm)	7	10	10		10
Pixels	1	8×8	4×4		8×8
A_{active} (mm^2)	$9^2 \pi$	53×53	22×22		53×53
A_{total} (mm^2)	$15.5^2 \pi$	59×59	27.5×27.5		61×61
Geom. eff. (%)	36	81	61		75
IAC (C/cm^2)	3.62 / 6.70	9.23 / 11.48 / 6.93	2.09	11.79 / 7.31	0.37
QE/QE_{orig} (%)	74 / 37	24 / 83 / 107	47	63 / 65	101
Comments	better vacuum; modified PC	ALD surfaces; 1- / 1- / 2-layer	film between 1^{st} & 2^{nd} MCP	ALD surfaces; film btw. 1^{st} & 2^{nd} MCP	ALD surfaces; film in front of 1^{st} MCP

desorbed from the MCP material. These and other residual gas atoms will be ionized and accelerated towards the PC. From the hard impact of the ions at the PC the substrate may get damaged and reactions can pollute the surface. This could lead to a gradual change in the work function which causes a degradation of the QE. Another suggestion for the cause of the PC aging is that neutral molecules in the residual gas like CO_2, O_2 or H_2O may react with the PC surface [12].

In a first attempt to reduce the aging the vacuum quality inside the tubes was improved and a treatment of the MCP surfaces with electron scrubbing was performed. Unfortunately these actions did not increase the lifetime of MCP-PMTs substantially. However, with new innovative approaches the manufacturers recently succeeded in significantly enhancing the lifetime of MCP-PMTs. The following techniques were applied:

- One of the first approaches was a thin (5 - 10 nm) Al_2O_3 protection film placed in front of the first MCP to stop feedback ions from reaching the PC. The disadvantage of this approach is a substantial reduction of the collection efficiency. Therefore, in later MCP-PMT models Hamamatsu put the film between the 1st and 2nd MCP layer.
- An attempt with a more robust PC was realized at BINP (Budker Institute of Nuclear Physics) in Novosibirsk, Russia. With a conventional bialkali PC baked in vapors of cesium and antimony a slower QE degradation was achieved [13]. However, this also led to a significantly increased dark count rate of more than 100 kHz/cm^2.
- An atomic layer deposition (ALD) technique was first suggested by Arradiance Inc. [14]. The surfaces of the MCP pores are coated with ultra-thin layers of resistive and/or secondary electron emissive (SEE) material to prevent the desorption of gaseous contaminants during the electron amplification process. An interesting side effect of this approach is the possibility of optimizing the MCP resistance and the SEE coefficient independently and by that increase the rate capability and the gain of the MCP-PMT. This technique was first applied in MCP-PMT prototypes from PHOTONIS and later by other customers [15]. Also in the latest MCP-PMT models from Hamamatsu and Photek this approach is pursued. Currently the ALD coating appears to be the most promising technique to reduce the PC aging and to increase the lifetime of MCP-PMTs.

3. Measurement setup

Only very few lifetime data for MCP-PMTs [16, 17] were available a few years ago. Even worse, the results of these measurements were difficult to compare since they were obtained in different environments. To allow a fair comparison of the aging of the new lifetime-enhanced MCP-PMT prototypes we have started a long-term simultaneous measurement of their lifetime in the year 2011. The sensors are permanently illuminated with photons at a rate comparable to that expected in the PANDA environment [18]. Over the years the MCP-PMTs listed in Table 1 were included in the setup. Gain, dark count rate and QE (as a function of the wavelength and of the PC surface) are measured in irregular intervals as a function of the IAC. This should allow a sound judgment on the best technique to prevent aging.

The illumination setup consists of a pulsed 460 nm LED whose light spot is widened by a thick lens to provide a wide and homogeneously lighted area at the plane where all MCP-PMTs are placed (see also [19]). In front of the MCP-PMTs the light is attenuated to the single photon level by neutral density filters. The LED pulse rate is 1 MHz and the gain of the MCP-PMTs is adjusted to roughly 10^6. The LED intensity is monitored with a photo diode and the MCP pulse heights are permanently recorded by a VME DAQ system at a highly prescaled rate. Spectral QE measurements in a wavelength band of 250 - 700 nm (in $\Delta\lambda = 2$ nm steps) are performed every few weeks with an in-house monochromator [20] which is powered by a stable xenon lamp. Every few months a complete surface scan across the PC is done in 0.5 mm steps for each MCP-PMT model at a wavelength of 372 nm.

4. Results

The results of the lifetime-enhanced MCP-PMTs with a film only (Hamamatsu R10754X-M16 JT0117) and a modified PC (BINP #1359 and #3548) are extensively discussed in [19]. The

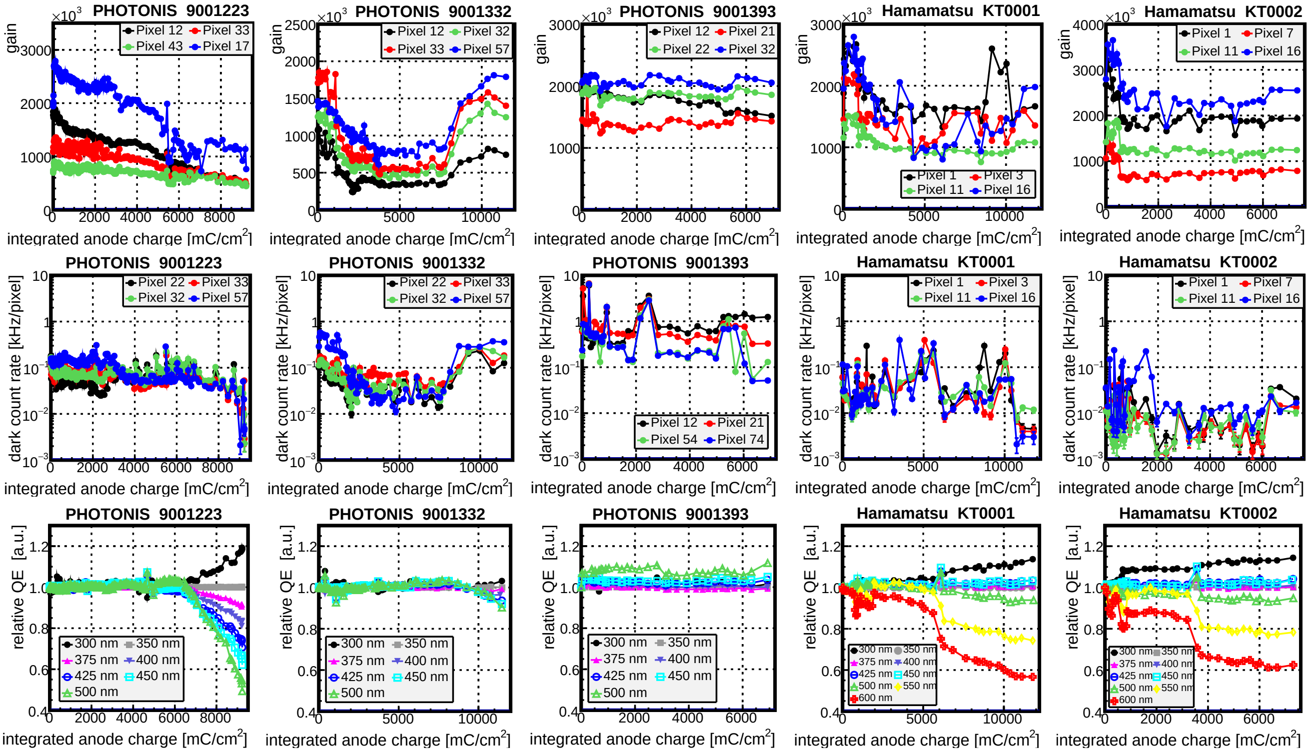

Figure 1: Gain [upper row], dark count rate [middle row] and relative QE [lower row] as a function of the IAC. Compared are the investigated MCP-PMTs with ALD coating (columns from the left): PHOTONIS XP85112 9001223, 9001332, 9001393, and Hamamatsu R10754X-M16M KT0001, KT0002.

main observations were an exponentially decreasing dark count rate and a wavelength dependent QE degradation in the MCP-PMT with film which indicates an effect on the PC work function. The surface scans revealed that the QE degradation starts at the rims and/or the corners of the PC and spreads slowly to the inner regions [8]. Here we will focus on the observations with the ALD coated MCP-PMTs.

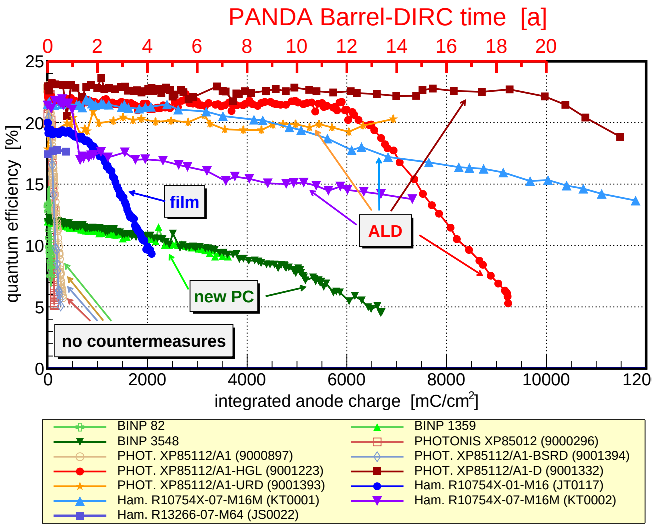

Figure 2: Comparison of the results of our lifetime measurements for different MCP-PMTs: QE as a function of the IAC at 400 nm.

In Figure 1 the gains, dark count rates, and relative QE (normalized to 350 nm) are plotted as a function of the IAC. Compared are the 5 ALD-coated MCP-PMTs illuminated during the lifetime measurement. In the left three columns the PHOTONIS two-inch tubes are shown, in the right two columns those from Hamamatsu (one-inch). There are some gain changes with increasing IAC (upper row) but these can easily be compensated by adjusting the high voltage during the operation. The most stable gain is observed with the PHOTONIS 9001393 with 2 ALD layers. There are also more or less severe fluctuations in the dark count rates (middle row) but with no obvious trends. This is in contrast to the dark count rates for the MCP-PMTs with a film and a modified PC as countermeasures against aging which show an exponential decline over several orders of magnitude pointing to a change of the PC work function [8, 21].

In the lower row of Figure 1 the relative QE of different wavelengths is displayed as a function of the IAC. One observes again that the QE drops faster for red than for blue light once the aging of the PC starts. This behavior is visible in a very pronounced way at >6 C/cm^2 in the PHOTONIS 9001223 and at >10 C/cm^2 in the PHOTONIS 9001332 MCP-PMTs. At this IACs the absolute QE also start to decline. The observed QE wavelength dependence also in the ALD coated MCP-PMTs is another indication that the PC work function changes while the PC gets hit by feedback ions. In the Hamamatsu MCP-PMTs a slow wavelength dependence of the aging is observed already from the beginning of the illumination.

A compilation of the QE of all tubes investigated to date is displayed in Figure 2. While the QE of older models (open dots on the very left) drops to <50% of the original value af-

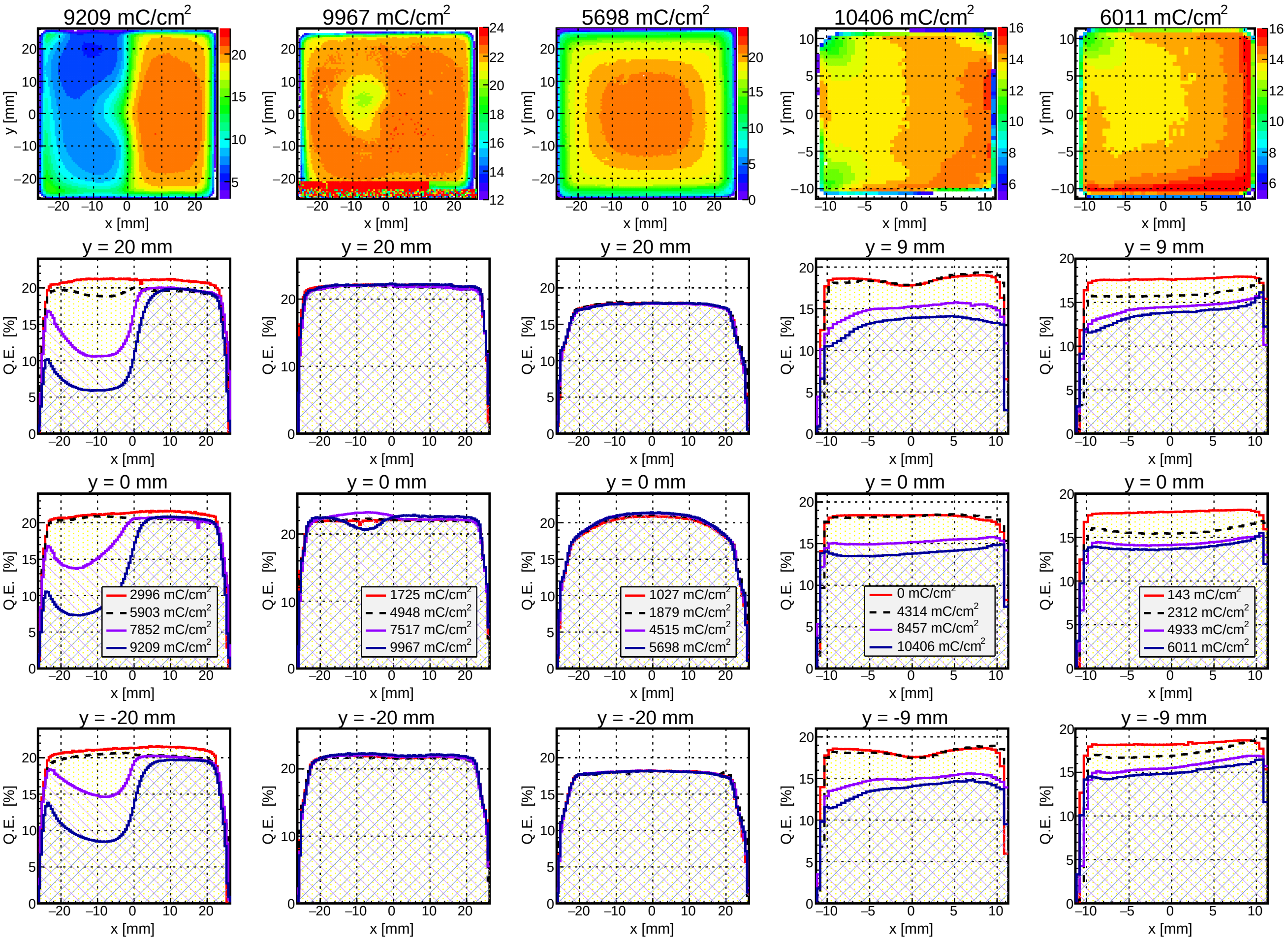

Figure 3: QE at 372 nm as a function of the PC surface for the ALD coated PHOTONIS two-inch and Hamamatsu one-inch MCP-PMTs. 1st column: PHOTONIS XP85112 9001223 (right PC half masked); 2nd col: PHOTONIS 9001332 (right PC half masked); 3rd col: PHOTONIS 9001393 (unmasked); 4th col: Hamamatsu R10754X-M16M KT0001; 5th col: Hamamatsu KT0002. Upper row: 2d QE charts (in % [color level]); other rows: QE x-projections at different y-positions and anode charges. For the interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.

ter <200 mC/cm^2 the situation for the latest lifetime-enhanced models (solid dots) is very different. The ALD coated PHOTONIS XP85112 (9001332) and Hamamatsu R10754X-M16M (KT0001) MCP-PMTs have meanwhile accumulated an IAC of >10 C/cm^2 with only minor to moderate QE degradations. This corresponds to 20 years of PANDA running and is an improvement of a factor 50 in the lifetime compared to former tubes.

For all investigated MCP-PMTs we have also measured the QE as a function of the PC surface. For the R10754X-M16 with a film and the MCP-PMTs with a more robust PC we observed that the QE degradation starts from the outer PC regions [8] and proceeds to the inner regions afterwards. The results of the QE surface scans for the 5 ALD-coated MCP-PMTs are displayed in Figure 3. The upper plots show the QE chart of the full PC surface with the IAC accumulated until January 2016 (see also the IAC values given in Table 1). For a better judgment of the magnitude of the observed QE changes three projections along the x-axis at different y-positions are plotted for each MCP-PMT. The histograms in these plots correspond to different anode charges, from an early stage of the illumination, when no QE degradation had occurred yet, to the highest IAC.

During the illumination one half of the two one-layer ALD coated PHOTONIS XP85112 MCP-PMTs (9001223, 9001332) was masked and not exposed to light. At $\sim$6 C/cm^2 the 9001223 developed QE degradations at the illuminated left half while the other side remained unaffected. The 9001332 shows the first sign of a QE degradation at the illuminated half at $\sim$10 C/cm^2 IAC. The fact that only the left unmasked halves of these MCP-PMTs show a declining QE are a strong indication that feedback ions are the main cause of the observed PC damage. The PHOTONIS MCP-PMT with two ALD layers (9001393) does not show any sign of QE degradation at close to 6 C/cm^2. The ALD coated Hamamatsu MCP-PMTs (KT0001 and KT0002) appear somewhat worse in their aging behavior. In both tubes a slow but continuous QE degradation is visible across the whole PC surface while in some corners the damage appears worse. This is consistent with observations made in [22].

5. Conclusions

Our long-term measurements of the latest lifetime-enhanced MCP-PMT models show that the tubes with ALD-coated MCPs are superior to those treated with other countermeasures against aging. The lifetime improvement of up to a factor 50 is tremendous. The surface scans suggest that the PC aging is mainly caused by feedback ions. The PHOTONIS 9001223 is a unique MCP-PMT with an aged and an unaged half of the PC and will be further investigated non-destructively with the goal of a better understanding of the aging process. Then it should become clearer whether work function changes or other processes are the real cause of the QE degradations. The new results can be considered as a breakthrough in the lifetime of MCP-PMTs and will have implications also on other experiments.

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