LIFETIME OF MICROCHANNEL-PLATE PHOTOMULTIPLIERS*

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The planned $\overline{\rm P}$ANDA experiment at the new FAIR facility requires a very good hadron identification, which will be achieved with two DIRC detectors. Microchannel-plate (MCP) photomultipliers (PMTs) are foreseen for the read-out of these devices, due to their usability in high magnetic fields of up to 2 T and their excellent time resolution. However, the lifetime under photon irradiation was not sufficient until recently, but the latest sensors seem to overcome this last restriction. We have tested the lifetime of several MCP-PMTs of different manufacturers under $\overline{\rm P}$ANDA conditions. The main goal was to achieve comparable data for all potential sensors simultaneously. The measurement procedure requires the permanent monitoring of the illumination and irregular interruptions after several days (typ. 3–10) to measure the dark count rate, gain and the spectral quantum efficiency of all sensors. On larger time scales of 2–4 months the whole surface of the sensors is scanned to determine faster aging areas. Our results reveal excellent lifetime performances for MCP-PMTs with MCPs coated by an atomic layer deposition (ALD) technique. Especially PHOTONIS XP85112/A1-HGL sensors seem to fulfill all requirements.

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1. Introduction

At the new FAIR facility [1] at GSI, antiproton beams of 1.5 GeV/c to 15 GeV/c momentum will be provided. This beam will be brought to collision with a proton target in the new $\overline{\rm P}$ANDA detector [2, 3]. One of the main physics goals of this experiment is charmonium spectroscopy

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with very high precision and the search for gluonic excitations. Among the detector requirements, the particle identification is crucial to achieve enough precision. Two DIRC (Detection of Internally Reflected Cherenkov light, [4]) detectors will provide pion/kaon separation of up to 4 GeV/c both in forward direction (endcap disc DIRC [5]) and around the interaction region (barrel DIRC [6, 7]).

The choice of photon sensors is limited due to the constraints given by the DIRC detectors. Both focal planes will reside in a high solenoidal magnetic field of up to 2 T prohibiting the application of standard PMTs. Silicon sensors cannot be used due to the high neutron flux. Further constraints are caused by the high luminosity of 2×10^{32} cm^{-2}s^{-1} of the $\overline{\text{P}}$ANDA detector. The expected average proton–antiproton reaction rate will be 20 MHz and the simulated measured photon rate will be 200 kHz cm^{-2} for the barrel DIRC and ≈ 1 MHz cm^{-2} for the disc DIRC. This results in an integrated anode charge of 5 C cm^{-2} for the barrel DIRC, assuming a 50% operation of $\overline{\text{P}}$ANDA over 10 years and a MCP gain of 1×10^6. For the disc DIRC, the lifetime requirements are correspondingly even more severe.

2. Reasons for aging of MCP-PMTs

During the illumination, the MCPs as well as the photo cathode are damaged. The aging of the MCPs has been known for more than 40 years [8] and caused mainly by feedback ions at very high gains. The deterioration of the MCPs results in a gain drop. An improvement came with the chevron-style arrangement of the MCPs, which is the default today. Combining two to three chevron-style MCPs with a photocathode leads to the currently available MCP-PMTs. Although a significant gain drop down to one third of the initial value can be measured, the lifetime of the tube itself is not limited by this, since a moderate gain drop can be compensated by applying a higher voltage.

However, aging of the photo cathode cannot be compensated and results in a decrease of the quantum efficiency and the dark count rate. Although a reduction of the dark count rate is desirable, it is correlated to the decrease of the quantum efficiency due to a rise of the work function for standard bi- and multi-alkali cathodes and indicates the deterioration process. Feedback ions from the MCPs and/or the residual gas are the origin of the aging. These can induce a vast amount of processes with the cathode, such as chemical reactions, adsorption and cluster-, lattice- or surface-defects, depending on the momentum and the type of the ion. Especially oxygen [9] and heavy ions, such as lead, seem to be problematic. Hence, to improve the lifetime of MCP-PMTs it is necessary to protect the cathode and/or make it more 'robust' to feedback ions.

3. Methods to increase the lifetime

We have investigated several sensors of three manufacturers which had different methods applied to increase the lifetime. Table I shows the investigated sensors concerning characteristics and illumination parameters. The abbreviations in the row 'Comments' will be discussed in the following.

TABLE I

Characteristics and illumination parameters of the investigated MCP-PMTs. Lifetime enhanced models are marked with (∗).

Manufacturer	PHOTONIS			BINP		Hamamatsu	
Type	XP85012	XP85112/A1	XP85112/A1-HGL(∗)		(∗)	R10754X-01-M16(∗)	R10754X-07-M16M(∗)
Serial no.	9000296	9000897	9001223 9001332	#82	#1359 #3548	JT0117	KT0001 KT0002
No. of pixels Active area [mm^2]	8×8 53×53	8×8 53×53	8×8 53×53	1 $9^2\pi$	1 $9^2\pi$	4×4 22×22	4×4 22×22
Total area [mm^2] Geometr. efficiency [%]	59×59 81	59×59 81	59×59 81	$15.5^2\pi$ 36	$15.5^2\pi$ 36	27.5×27.5 61	27.5×27.5 61
Comments	vac	vac, ES	vac, ES, **ALD**	PL1	**PC**	**PL2**, CI	**ALD**
Max. differential charge [mC $cm^{-2}d^{-1}$]	4.0	3.4	13.5 13.6	2.95	10.7 11.7	14.1	19.3 10.9
Illuminated area [%]	100	100	50	100	100	100	100

Obviously, the flux of neutral gases can be reduced by improving the vacuum of the tube (vac) and heating the MCP to outgas diffused molecules and atoms. High electric fields at surface spikes of the MCP can result in higher ion fluxes. Electron scrubbing (ES) can be applied to reduce the amount/size of these spikes by cleaning and polishing the surface.

In addition, each company tried different methods for their latest models:

— The Budker Institute of Nuclear Physics (BINP) in Novosibirsk baked their photocathode (PC) of $Na_2KSb(Cs)$ in a vapor of cesium and antimony. This treatment results in an increased resistance against feedback ions, but increases the dark count rate significantly. Previous models were equipped with a protection layer in front of the first MCP (PL1). Unfortunately, this reduces the collection efficiency. A positive effect could not be observed, probably due to manufacturing difficulties.

— PHOTONIS coated their MCPs with a thin layer of material with a high secondary emission coefficient. This atomic layer deposition (ALD) [10] technique results in a significantly higher gain and a lower secondary electron energy, and finally a lower probability for ion production [11]. In addition, this leads to a sealing of the MCP and can prevent desorption of gaseous contaminants [11, 12].

— Hamamatsu applied a protection layer, between the first and the second MCP (PL2) to some of their sensors. Thus, the collection efficiency remained unchanged. An additional ceramic insulation (CI) around the MCP should prevent bypassing residual gas molecules [9]. The latest models were also equipped with an ALD layer.

4. Setup of lifetime measurements

The main goal of our lifetime measurements was to get data comparable to a situation in an environment of a high energy physics experiment. The setup was described in previous papers [13, 14], but a short overview will be given in the following. Several MCP-PMTs are simultaneously illuminated with a pulsed LED at 460 nm, whose intensity is attenuated to single photon level. In contrast to measurements of the manufacturers, which are performed with a DC light source within a few weeks, the sensors were operated within the proposed specification limits. The major drawback is a very long measurement time of up to 2.5 a for the XP85112/A1-HGL 9001223 so far. During the illumination, the signals were constantly monitored with a CAMAC-DAQ to determine the collected charge. Every few days ($\approx$ 7 d) the illumination is interrupted to measure gain and dark count rate. An in-house monochromator with a gauged reference diode is used to determine the spectral quantum efficiency [15]. On larger time scales of 2–4 months, the whole surface of the sensors is scanned with a laser (372 nm, ∅ ≈ 1 mm) to identify faster aging areas. The active areas of all sensors were fully illuminated, except for both PHOTONIS XP85112/A1-HGL, where the area was half covered to see if there are any differences in the aging of the illuminated to the unilluminated areas.

5. Results

The aging is a function of the collected anode charge. In the following, the results will be shown only for to the latest lifetime enhanced MCP-PMTs. Figures 1 and 2 show the dark count rate and gain for the sensors with improved photo cathode (top left) and protection layer between both MCPs (lower left) compared to MCP-PMTs with ALD. A decline of the dark count rate of two orders of magnitude is clearly visible compared to the ALD coated ones which stay more or less constant. Furthermore, no difference between the covered and uncovered areas is observed. For the Hamamatsu R10754X-07-M16M, the dark count rate has significantly changed compared to the R10754X-01-M16, but more data are needed.

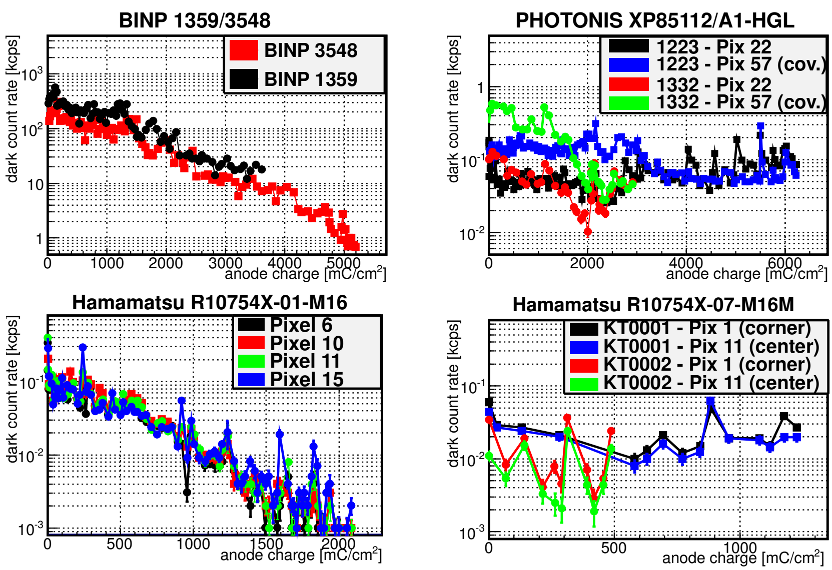

Fig. 1. Dark count rate for lifetime enhanced MCP-PMTs.

All lifetime improved sensors show only a small gain decrease or none at all. So far, the gain is unchanged for both Russian and both ALD coated sensors of Hamamatsu. The R10754X-01-M16 dropped by about 30% and the PHOTONIS XP85112/A1-HGL by about 50%. In real experiments, this can be easily compensated by applying a higher voltage.

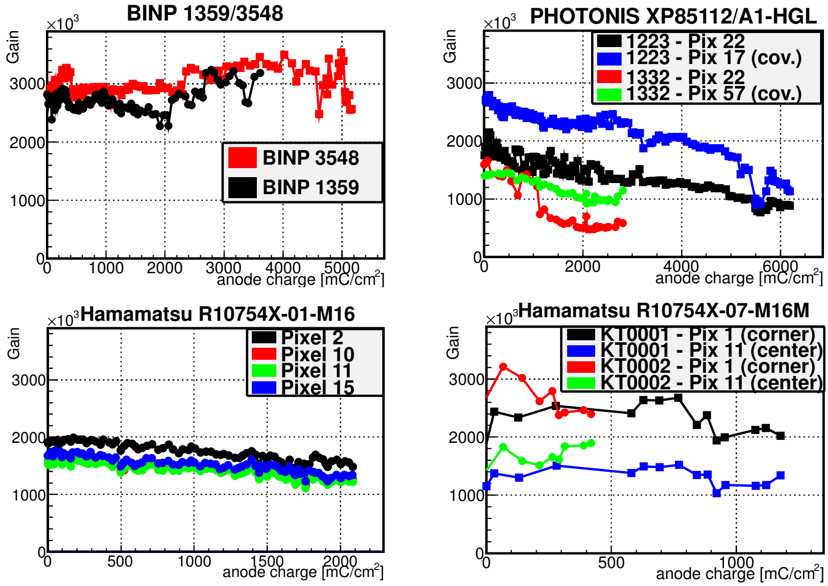

Fig. 2. Gain for lifetime enhanced MCP-PMTs.

The more important aging parameter is the change of the quantum efficiency (QE), since any decrease cannot be compensated. Figure 3 illustrates the changing of the QE for different wavelengths. It has dropped continuously since the beginning for the BINP #3548, whereas for the R10754X-01-M16 the degradation has started at about 800 mC cm^{-2} and then dropped more rapidly until the end. The QE of the PHOTONIS XP85112/A1-HGL 9001223 stayed constant until ≈ 5.9 C cm^{-2} and the aging started just recently. Both ALD coated MCP-PMTs of Hamamatsu still lack some data, but the lifetime has increased compared to R10754X-01-M16. The aging is more obvious if the relative degradation is normalized to a specific wavelength. We define

$$\text{rel. } QE_\lambda(Q) = \frac{QE_\lambda(Q)}{QE_\lambda(0)} \Bigg/ \frac{QE_{\lambda_0}(Q)}{QE_{\lambda_0}(0)}\,; \qquad (\lambda_0 = 350 \text{ nm})\,. \qquad (1)$$

This fraction is smaller than 1, if the decrease is faster than for a specific wavelength λ_0. The Hamamatsu R10754X-01-M16 in Fig. 4 clearly reveals a faster aging at higher wavelengths. For the BINP #1358 and #3548 with a different cathode material and for the ALD coated MCP-PMTs, no deviation from 1 is measured until now. The result of the R10754X-01-M16 indicates a change of the work function during the aging process and is strongly correlated to the change of the dark count rate.

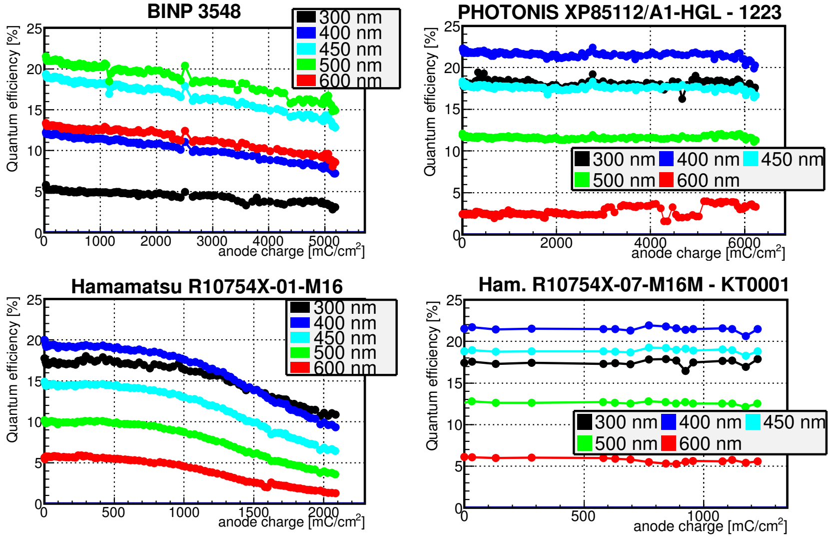

Fig. 3. Quantum efficiency for several MCP-PMTs.

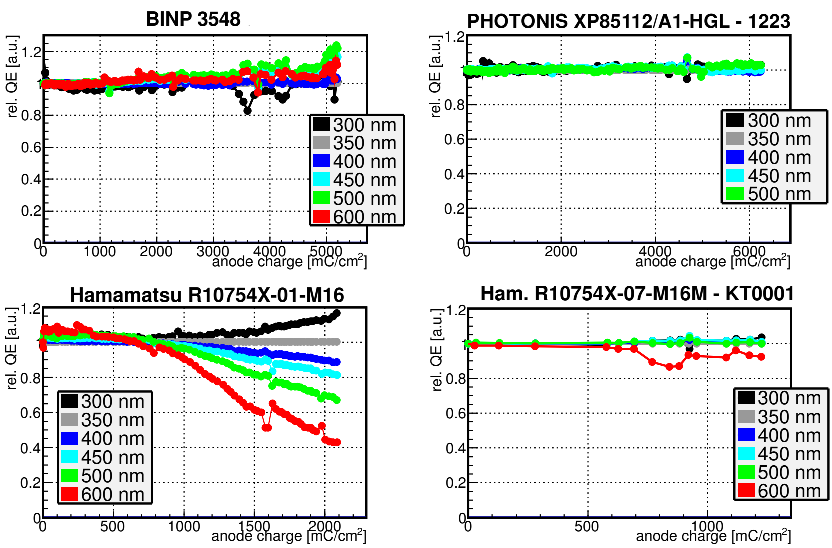

Fig. 4. Relative QE degradation normalized to 350 nm.

Furthermore, the QE degradation is position dependent. Figure 5 shows the results for the QE-scans at the beginning (top row), the latest/last measurement (middle row), and a horizontal slice at a fixed y position for several scans (bottom row) for the R10754X-01-M16, the BINP #3548 and the XP85112/A1-HGL 9001223 (left to right). The two dimensional plots are scaled to their relative cathode sizes. The boundary between the covered area on the right side of the XP85112/A1-HGL 9001223 and the uncovered one on the left is indicated by a black line. Obviously, the aging starts at the corner(s) or the rim of each sensor. The right (covered) side of XP85112/A1-HGL 9001223 is less damaged, since no or at least far less photon-induced feedback ions are produced.

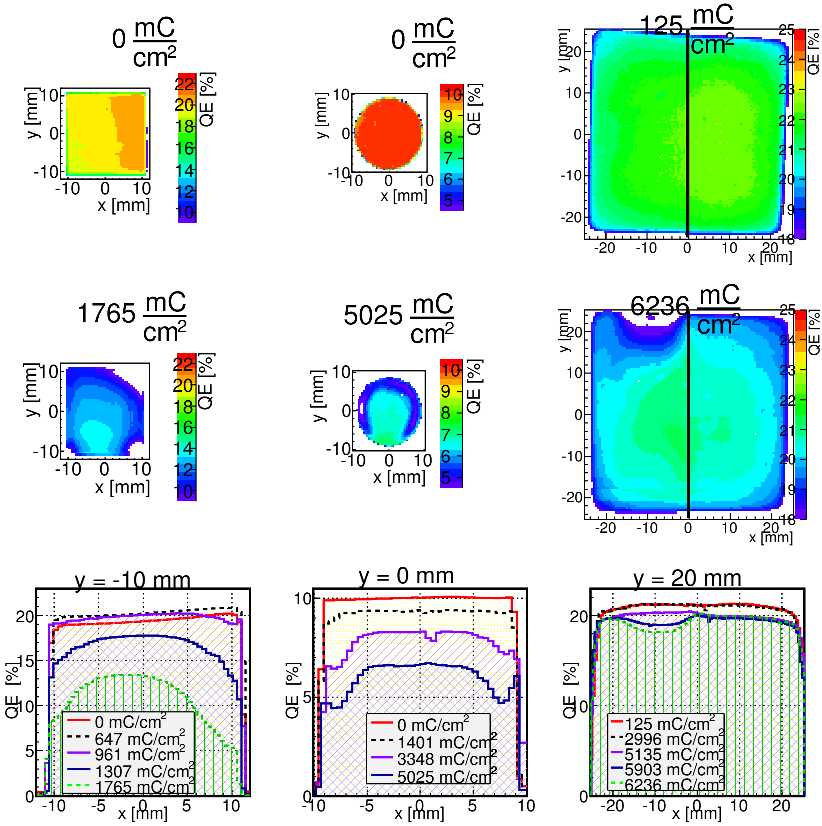

Fig. 5. Spacial QE@372 nm for R10754X-01-M16 (left), BINP #3548 (center) and XP85112/A1-HGL 9001223 (right). All two dimensional plots are scaled to the relative sensor dimensions.

Finally, a comparison to previous measurements is given in Fig. 6. Obviously, all new methods have increased the lifetime of MCP-PMTs compared to the former devices. These were unusable after < 200 mC cm^{-2}. The QE of the BINP #3548 diminished constantly and is still above 50% at ≈ 5 C cm^{-2}. The R10754X-01-M16 with protection layer was completely depleted at 2.0 C cm^{-2}, while the ALD sensors of Hamamatsu do not show any aging up to 1.2 C cm^{-2} so far. The ALD coated PHOTONIS MCP-PMTs show almost no damage up to $\approx$ 5.9 C cm^{-2} and $\approx$ 2.9 C cm^{-2} resp. Just recently, the first indications of aging are visible for one sensor above 6.0 C cm^{-2}. This sensor has successfully surpassed the requested 10 a of operation under $\overline{\text{P}}$ANDA barrel-DIRC conditions at maximum luminosity.

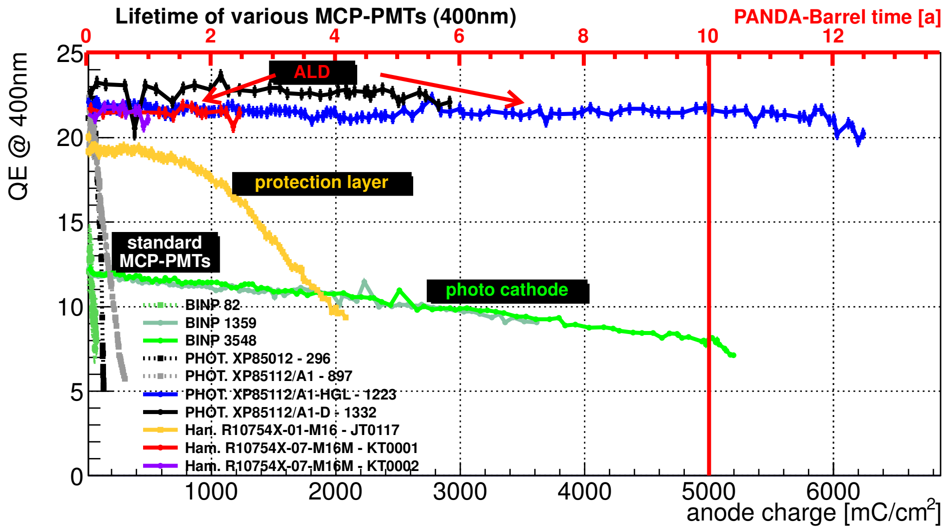

Fig. 6. QE@400 nm for several MCP-PMTs as a function of the integrated anode charge.

6. Conclusions

Our lifetime measurements under realistic high energy physics conditions show clearly the striking improvements in the production of the latest MCP-PMTs. All approaches led to an increase of at least one order of magnitude. The best performance is achieved by ALD coated devices, but the complementary approach of a different photo cathode of BINP is also interesting. If the manufacturers manage to produce a sensor with an enhanced photo cathode and ALD coating, this one might be even superior.

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