Improved lifetime of microchannel-plate PMTs

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Abstract

The charged particle identification at the PANDA experiment will be mainly performed with DIRC detectors. Because of their advantageous properties the preferred photon sensors are MCP-PMTs. However, until recently these devices showed serious aging problems which resulted in a diminishing quantum efficiency (QE) of the photo cathode. By applying innovative countermeasures against the aging causes, the manufacturers recently succeeded in drastically improving the lifetime of MCP-PMTs. Especially the application of an ALD coating technique to seal the material of the micro-channels proves very powerful and results in a lifetime of $\approx$6 C/cm^2 integrated anode charge without a substantial QE degradation for the latest PHOTONIS XP85112. This paper will present a comparative measurement of the lifetime of several older and recent MCP-PMTs demonstrating this progress.

Keywords: PANDA experiment, microchannel plate photomultipliers, single photons, lifetime, ALD coating

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1. Introduction

The PANDA experiment [1] at the new FAIR accelerator at GSI will perform charmonium spectroscopy and search for gluonic excitations using high luminosity antiproton beams from 1.5 to 15 GeV/c. These and other scientific goals require a high performance kaon/pion separation up to 4 GeV/c. Because of space limitations the main components of the charged particle identification system will consist of DIRC (Detection of Internally Reflected Cherenkov light) detectors [2]: a barrel DIRC [3] cylindrically surrounding the interaction region and an endcap disc DIRC [4] in the forward direction.

The image planes of both DIRCs will reside inside the solenoidal magnetic field of up to 2 Tesla and the average antiproton-proton annihilation rate is anticipated to reach 20 MHz. These conditions require an efficient single photon detection inside the B-field at photon densities of $\approx$200 kHz/cm^2 for the barrel DIRC and >1 MHz/cm^2 for the disc DIRC. For a sufficient resolution in the Cherenkov angle reconstruction a pixel size of $\approx$5x5 mm^2/pixel for the barrel DIRC and even better for the disc DIRC is needed. Moreover, a time resolution of <100 ps is required to enable a dispersion correction in the radiators and to measure the time-of-propagation of the Cherenkov photons. There are only very few sensors capable of fulfilling these constraints.

The favored sensors for the PANDA DIRCs are microchannel plate (MCP) photo multipliers (PMT). Until recently, however, these devices showed serious deficiencies in terms of rate capability and lifetime. The problem of a limited photon rate capability in principle can be tackled by reducing the MCP recovery time by using lower resistive materials for the pores and >1 MHz/cm^2 were reached without any gain drop [5]. Nevertheless, the aging problem remained an issue.

2. Methods for lifetime improvement

Aging of an MCP-PMT usually manifests itself in a reduction of its gain, its dark count rate and in particular its quantum efficiency (QE) when the integrated anode charge accumulates. While a lower dark count rate is desirable and the reduced gain can usually be compensated by a higher PMT voltage, the diminishing QE may lead to an unusable tube. The main cause of the QE drop appears to be back-flowing ions from the rest gas, especially hydrogen, which impinge on the photo cathode (PC) and damage it. It was also speculated that neutral rest gas molecules like oxygen and carbon dioxide may pollute the PC surface and change its work function [6].

An obvious way of reducing the amount of rest gas in the tube is to bake the micro-channel plates to outgas the glass material

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Table 1: Characteristics of the investigated lifetime-enhanced MCP-PMTs. Also shown is the currently accumulated anode charge of each measured MCP-PMT.

Manufacturer	BINP	PHOTONIS	Hamamatsu	Hamamatsu
Type		XP85112/A1-HGL	R10754X-01-M16	R10754X-01-M16M
Counter ID	#1359 / #3548	9001223 / 9001332	JT0117	KT0001 / KT0002
Pore diameter (μm)	7	10	10	10
Number of pixels	1	8×8	4×4	4×4
Active area (mm^2)	$9^2\ \pi$	53×53	22×22	22×22
Total area (mm^2)	$15.5^2\ \pi$	59×59	27.5×27.5	27.5×27.5
Geometrical efficiency (%)	36	81	61	61
Comments	better vacuum; new photo cathode	better vacuum; ALD surfaces	film between 1^{st} & 2^{nd} MCP	ALD surfaces
Integrated anode charge (mC/cm^2)	3616 / 5025	5903 / 2375	2086	842 / 215

and to increase the vacuum inside the MCP-PMT. In addition the manufacturers often apply electron scrubbing to clean and polish the MCP surfaces. Besides these approaches the three main manufacturers of MCP-PMTs apply the following techniques to prolong the QE lifetime:

- In their latest MCP-PMT models the Budker Institute of Nuclear Physics (BINP) in Novosibirsk applies a special treatment to the bi-alkali PC which is baked in a vapor of cesium and antimony. This seems to increase the PC's hardness against feedback ions, but significantly increases the dark count rate of the tube [7].
- A new and innovative approach is pursued by PHOTONIS. The surfaces and pores of the MCPs are coated with a very thin layer of secondary electron emissive material by applying an atomic layer deposition (ALD) technique [8]. This layer is expected to significantly reduce the outgassing of the MCP material.
- Hamamatsu first tried to eliminate the ion backflow from the anode side of the MCP-PMT by putting a thin protection layer of aluminum between the two MCPs. In addition, potential gaps between the MCPs and the metal walls of the tube frame were sealed with ceramic elements to hinder neutral atoms and molecules from the back part of the MCP-PMT in reaching the PC [6]. In their most recent MCP-PMTs Hamamatsu also applies the ALD technique.

In the recent years we have measured the lifetime of several MCP-PMTs of the three manufacturers mentioned above. The first tubes from BINP (#82) and PHOTONIS (XP85012-9000298 and XP85112-9000897) were still without the most recent improvements. A list of the characteristics of the MCP-PMTs discussed in this paper are given in Table 1.

3. Properties of new MCP-PMTs

In recent papers we have shown that with 10 μm MCP-PMTs single photons can be efficiently detected in magnetic fields of up to 2 Tesla, even if the field direction does not exactly point along the PMT axis [9, 10]. For the ALD coated MCP-PMTs we measure a substantially higher gain than with the untreated ones which is probably due to a higher gain factor of the secondary electron emissive material on the pores.

The time resolution of all investigated MCP-PMTs is better than 50 ps (σ), if one does not take into account the tails in the distribution arising from back-scattered electrons at the MCP entrance [10, 11]. No dependence of the time resolution on the magnetic field was observed [12].

The multi-anode MCP devices show gain variations of typically a factor 2 for the PHOTONIS PMTs and somewhat worse for those of Hamamatsu, where even significant gain variations within the same pixel [10] were observed. The new ALD coated MCP-PMTs currently show worse gain variations, whose origin is being investigated. The cross talk between adjacent pixels is moderate [10, 11] and tolerable for the PANDA DIRCs.

The rate capability of the most recent MCP-PMTs of Hamamatsu and PHOTONIS is >1 MHz/cm^2 with no gain change [13]. This is sufficient for both PANDA DIRCs.

4. Lifetime

Until recently only few quantitative results on the lifetime of MCP-PMTs were available [14, 15]. Moreover, these were obtained in very different environments and therefore difficult to compare. The standard way of measuring the lifetime of an MCP-PMT is to determine the gain and especially the QE as a function of the integrated anode charge. If the QE has dropped by a certain percentage (e.g. 50%) of its original value the sensor is presumed unusable. The PANDA experiment is expected to run for at least 10 years at a 50% duty cycle. Assuming the antiproton-proton annihilation rate of 20 MHz and a sensor gain of 10^6, simulations show the following integrated anode charges to be expected for the MCP-PMTs: 5 C/cm^2 for the barrel DIRC and, even with a filter on the allowed wavelength band, more for the disc DIRC.

The lifetimes we determined for the first MCP-PMTs of BINP (#82) and PHOTONIS (XP85012-9000298 and XP85112-9000897) were by far not enough for PANDA. The QE had dropped by >50% after only ≈200 mC/cm^2 integrated anode charge [12, 16].

4.1. Setup

The setup of our lifetime measurements was described several times in other papers [16, 17]. The MCP-PMTs are permanently and simultaneously illuminated with a blue LED at a single photon rate comparable to that expected for PANDA. At a highly prescaled rate the signal charges are continuously monitored and recorded using a CAMAC DAQ. Every few days gain and dark count rate of each MCP-PMT are measured and a wavelength scan of the QE is performed using an in-house monochromator with a reference diode [18]. In intervals of a few months the photo current across the whole PC surface is measured in small steps of 0.5 mm at a wavelength of 372 nm to identify regions with a degraded QE for each MCP-PMT.

4.2. Results

Important quantities for Cherenkov detectors are gain and dark count rate of the used sensors. The gain has to be high enough for single photon detection and the dark count rate should be low since the photon yield per track is usually rather moderate. These quantities were measured as a function of the integrated anode charge as shown in Fig. 1. We observe that the gain changes are only moderate for all displayed sensors and can easily be compensated for by increasing the tube voltage. On the other hand the dark count rate drops by two orders of magnitude for the BINP and Hamamatsu MCP-PMTs. This finding indicates a change of the PC work function during the illumination of the sensor. The PHOTONIS XP85112 does not show this change in the dark count rate.

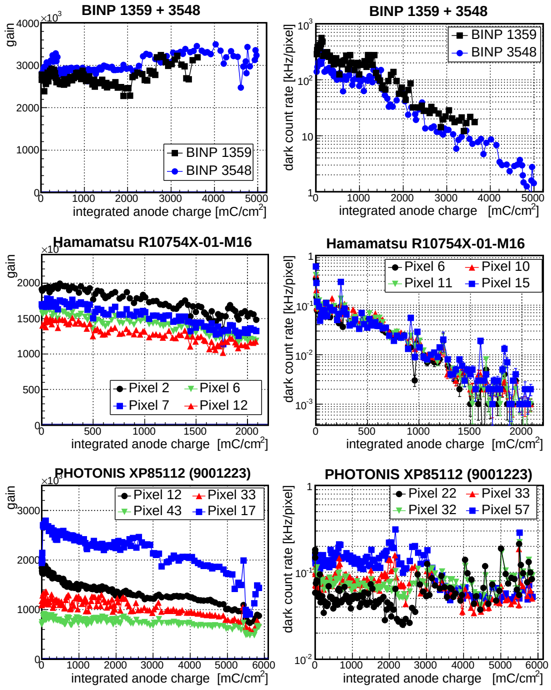

Figure 1: Gain (left) and dark count rate (right) as a function of the integrated anode charge for selected MCP-PMTs.

The results of the QE scans across the PC surface are displayed in Figs. 2 to 4 for three MCP-PMTs. The upper left plot always shows a QE chart of the full PC surface with the anode charge accumulated at the time of writing this paper. For a better judgement of the magnitude of the observed QE changes three projections along the x-axis at different position of y are plotted for each MCP-PMT. The histograms in these plots correspond to different anode charges, from the very beginning of the illumination to the highest charge. It is obvious that the MCP-PMTs from BINP (#3548, Fig. 2) and Hamamatsu (R10754X, Fig. 3) show clear QE damages. From the QE chart and its projections it appears that the QE degradation starts at the corners (R10754X) or at the rim (#3548) of the sensor. With progressing illumination the QE drop extends more and more to the inner regions of the PC. After an anode charge of 5025 mC/cm^2 and 1765 mC/cm^2 for the BINP and Hamamatsu MCP-PMT, respectively, the QE has dropped by more than 50% of its original value in certain regions. The situation is different for the ALD coated PHOTONIS XP85112 (Fig. 4), where only moderate QE degradations of 1-2% at 5.1 C/cm^2 are visible. Beyond this charge the sensor starts showing more QE damage across the surface, but still at a tolerable level. At 5.9 C/cm^2 a clear step emerges around x = 0 mm. This stems from the fact that the right half of the PC (x > 0 mm) of the sensor was covered during the illumination process. The effect of a rising QE on the left side of the PC (x < 0 mm) at increasing anode charges was already observed with another MCP-PMT from PHOTONIS [16].

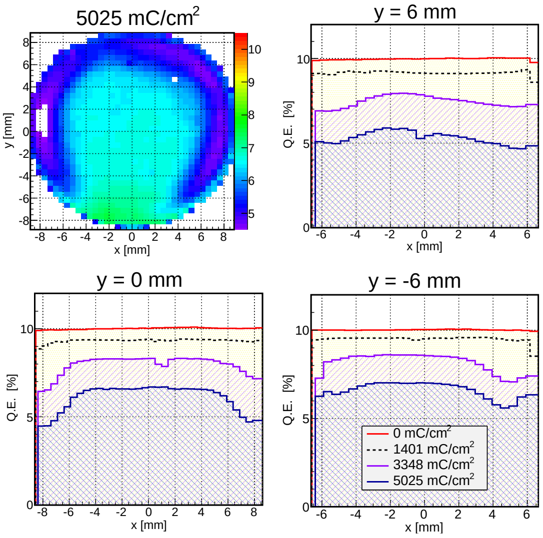

Figure 2: QE at 372 nm as a function of the PC surface for the BINP #3548 MCP-PMT with an active area of 18 mm diameter. Upper left: two-dimensional QE chart (in % [color level]); other plots: QE x-projections at different y-positions and anode charges.

It was reported earlier [14, 16] that the QE degrades faster for red than for blue light. To study this observation we have measured the spectral QE dependence on the integrated anode charge for all investigated new MCP-PMTs. The results for different wavelengths are displayed in Fig. 5, the absolute QE (left column) and the QE relative to 350 nm (right column). It is obvious from the plots that the MCP-PMTs of the three manufacturers behave differently. While the QE of the Hamamatsu R10754X with ion barrier starts dropping significantly beyond ≈1 C/cm^2 the QE of the BINP #3548 with its modified PC shows a constant decline up to 5 C/cm^2 and the PHOTO-

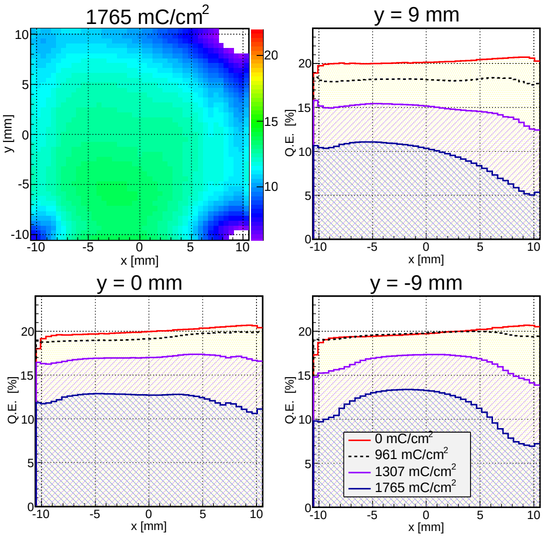

Figure 3: QE at 372 nm as a function of the PC surface for the Hamamatsu R10754X-01-M16 (JT0117) MCP-PMT with an active area of 22 x 22 mm^2. The four plots display the same properties as in Fig. 2.

NIS XP85112 shows almost no degradation of the QE up to 5.9 C/cm^2. A spectral dependence of the QE drop is only seen in the R10754X which again points to a change in the work function of the PC, possibly due to rest gas molecules adsorbed at the PC surface. Both the new BINP and PHOTONIS MCP-PMTs do not exhibit a QE dependence on the wavelength.

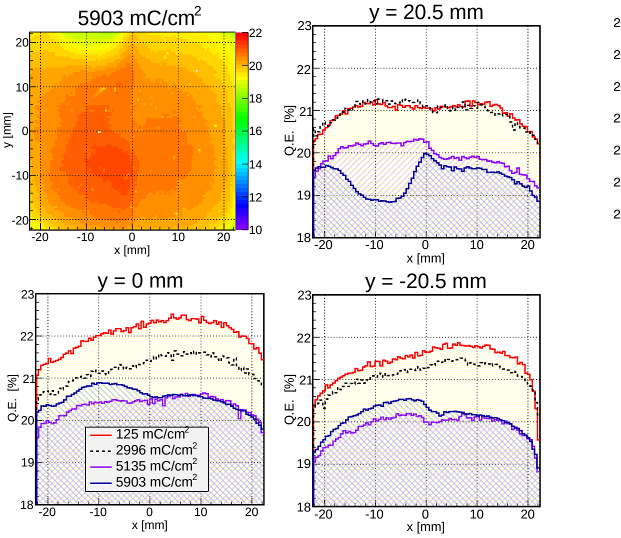

Figure 4: QE at 372 nm as a function of the PC surface for the PHOTONIS XP85112 (9001223) MCP-PMT with an active area of 53 x 53 mm^2. The four plots display the same properties as in Fig. 2.

Finally, in Fig. 6 the QE at 400 nm is compared for all investigated MCP-PMTs. Clearly, the older MCP-PMTs (open symbols) show a fast declining QE which drops below 50% after <200 mC/cm^2. The situation is very different for the new lifetime-enhanced tubes. The QE of the Hamamatsu R10754X-01-M16 with protection film is exhausted at <2 C/cm^2, while for the new ALD coated devices (R10754-07-M16M) there is no QE drop visible, though the accumulated anode charge is still below 1 C/cm^2. The QE of the two BINP MCP-PMTs (#1359 and #3548) is continuously diminishing up to ≈5 C/cm^2. For the new ALD coated PHOTONIS MCP-PMTs there is only a very moderate drop in QE, with one tube having been exposed to meanwhile 5.9 C/cm^2 and the second, later included in the measurement, to 2.4 C/cm^2. The accumulated anode charge of the first PHOTONIS tube corresponds to >10 years of running the barrel DIRC at the highest PANDA luminosity.

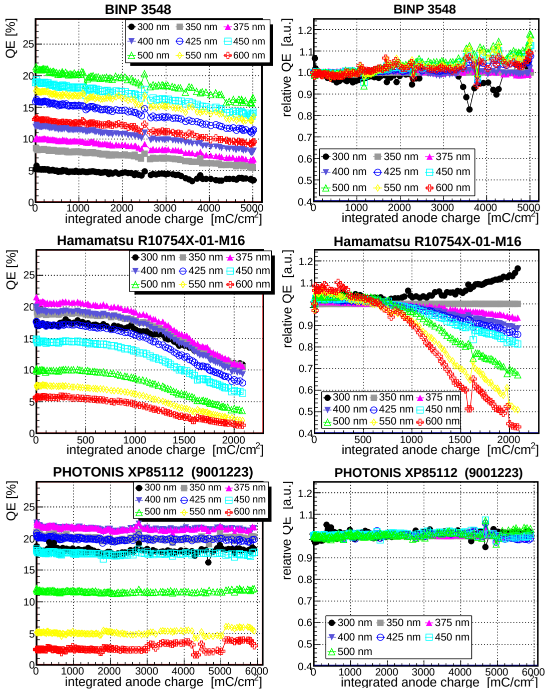

Figure 5: QE (absolute and relative to 350 nm) as a function of the integrated anode charge and for different wavelengths.

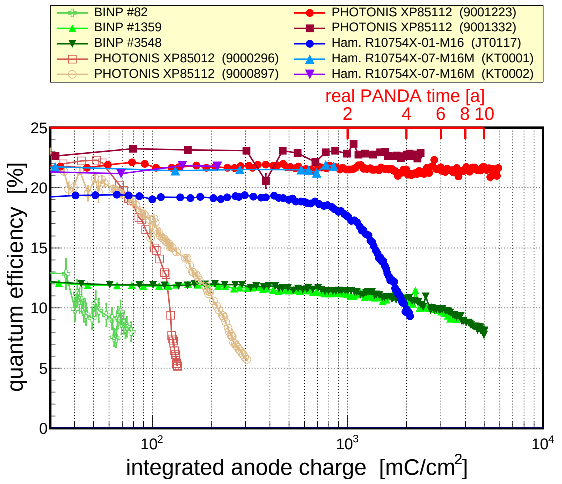

Figure 6: Comparison of our MCP-PMT measurements: quantum efficiency as a function of the integrated anode charge at 400 nm.

5. Conclusions

Our comparative measurements of the lifetime of MCP-PMTs show clearly the enormous improvements of the most recent devices. The countermeasures against aging taken by the different manufacturers led to an increase of the lifetime by an order of magnitude and more. The most important observations are the fact that the ALD coated tubes show the best QE behavior and that the modified PC of the BINP tube also shows a significant improvement concerning the hardness against ion backflow. An interesting option would certainly be to build an MCP-PMT which combines the ALD coating technique and the new PC from BINP.

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