Latest Improvements of Microchannel-Plate PMTs

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Abstract

The DIRC detectors of the P̄ANDA experiment at FAIR will use multi-anode MCP-PMTs as photon sensors. After long and extensive R&D work the performance parameters of the recent 2” MCP-PMT models are converging towards the required values. The lifetime of most ALD-coated MCP-PMTs is well surpassing the DIRC requirements with the best tube currently reaching >22 C/cm^2 without aging. The performance of the most advanced MCP-PMTs from PHOTONIS and Hamamatsu fulfill basically all requirements with a highlight being the high DQE of almost 30% for the PHOTONIS 9002108. The improvements of the latest MCP-PMT models compared to former tubes are emphasized in this paper. In addition, some performance features of a recently developed 2” MCP-PMT by Photek Ltd are presented and discussed.

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

1. Introduction

Microchannel-plate photomultipliers (MCP-PMTs) are identified as the only suitable sensors for the particle identification (PID) detectors of the P̄ANDA experiment [1] at the FAIR accelerator complex at GSI. Among other important physics goals [2] the P̄ANDA detector is built for a precise spectroscopy of charmonium and exotic matter states like glue-balls and hybrids. This requires excellent π/K separation to 4 GeV/c why, since the P̄ANDA detector is very compact, two Cherenkov detectors of the DIRC type [3] were chosen for PID. The focal plane of both detectors, a barrel DIRC surrounding the interaction region [4, 5] and an endcap disc DIRC covering the forward hemisphere [6, 7], will reside inside a magnetic field of >1 T which requires appropriate radiation hard photon sensors. In addition, $\lesssim$100 ps RMS time resolution, <1 kHz/cm^2 dark count rate (DCR) and ~1 MHz/cm^2 photon rate capability are needed leaving MCP-PMTs as the only photon sensor option.

2. Aging and lifetime

Until some years ago the major drawback of MCP-PMTs has been a serious aging problem [8, 9] caused by feedback ions from the residual gas hitting and damaging the photo cathode (PC). This resulted in a rapid decrease of the quantum efficiency (QE) as the integrated anode charge (IAC) increased. The major breakthrough against this came by the application of an atomic layer deposition (ALD) technique [10] where the MCP pores are coated with an ultra-thin layer of alumina or magnesia to reduce the outgassing of the MCP substrate. This led to a drastic increase of the lifetime of the latest MCP-PMTs [11, 12].

In the high photon rate environment of the P̄ANDA DIRCs the MCP-PMTs have to survive an IAC of $\gtrsim$5 C/cm^2 whereas former tubes had lost 50% of their original QE after <0.2 C/cm^2 (upper right corner of Fig. 1). Our long-term illumination [13] of various MCP-PMTs (for a list of the measured ALD-coated tubes see Table 1) with about the anticipated DIRC photon rates shows that most of the ALD-coated tubes reach the P̄ANDA required lifetime of 5 C/cm^2 IAC while the best MCP-PMT from PHOTONIS is meanwhile exceeding 22 C/cm^2 IAC. This is a factor 100 improvement compared to the former PMTs.

The data in Fig. 1 show the results of our on-going lifetime measurements for Hamamatsu (upper) and PHOTONIS (lower) MCP-PMTs. The ALD-coated 1” Hamamatsu PMTs (KT0001, KT0002) were equipped with an additional protection film between the first and second MCP-layer and revealed a slow but steady QE decrease. The first prototypes of the later developed 2” tubes with a film in front of the first MCP (JS0018, JS0022) showed a rather fast QE drop while the later devices (JS0027, JS0035) do not show aging signs to date. Also the most recent Hamamatsu tube without a film (YH0250) is undamaged after almost 4 C/cm^2 IAC. The first purely ALD-coated MCP-PMT (no film) surpassing 5 C/cm^2 IAC without PC damage was the PHOTONIS 9001223, while the 9001332 reached even 10

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

Manufacturer	PHOTONIS			Hamamatsu			
Type	XP85112	XP85112	XP85112	R10754X-M16M	R13266-M64	R13266-M768	R13266-M64
Sensor ID	9001223 / -1332	9001393	9002108	KT0001 / -02	JS0022 / -35	JS0018 / -27	YH0250
Pixels	8×8			4×4	8×8	8×128	8×8
Pore size (µm)	10			10	10		
A_{active} (mm^2)	53×53			22×22	51×51		
A_{total} (mm^2)	59×59			27.5×27.5	61×61		
Geom. eff. (%)	81			61	70		
IAC (C/cm^2)	9.23 / 15.91	22.15	1.17	20.09 / 19.33	4.92 / 8.69	1.28 / 3.56	3.85
QE / QE_{orig} (%)	24 / 36	104	75	24 / 24	26 / 97	14 / 92	97
peak QE / CE (%)	23 / ~65	20 / ~65	22 (30) / >90	21 / ~75	25 / ~40	23 / ~40	25 (30) / ~65
Comments	1 ALD-layer; no film	2 ALD-layers; no film	1 ALD-layer; no film	ALD and film btw. 1^{st} & 2^{nd} MCP	1 ALD-layer and film in front of 1^{st} MCP		1 ALD-layer; no film

C/cm^2 IAC. The best performing MCP-PMT to date (PHOTONIS 9001393) is equipped with two ALD-layers and does not show any sign of aging at >22 C/cm^2 IAC. Unfortunately, the most advanced PHOTONIS 9002108 shows PC damage already after <1 C/cm^2 IAC. The reason for this has yet to be clarified.

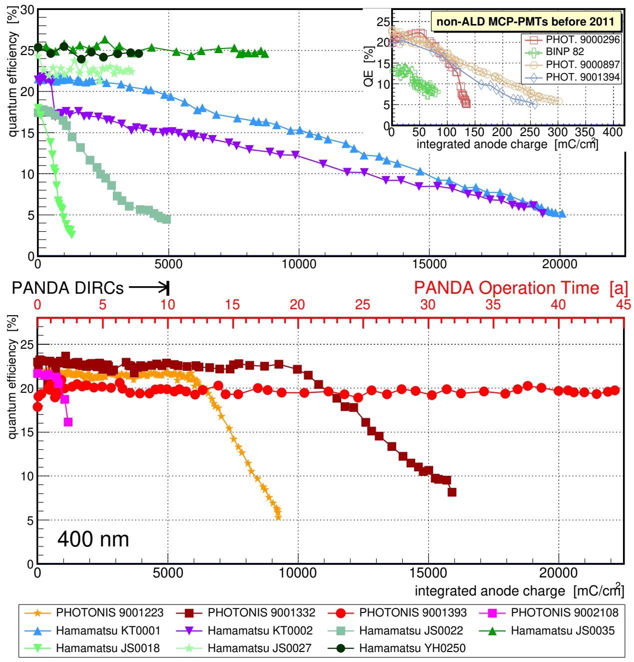

Figure 1: Results of our lifetime measurements for various MCP-PMTs: QE as function of IAC at 400 nm for ALD-coated Hamamatsu (upper) and PHOTONIS (lower) tubes and previous non-ALD devices (upper right corner).

In Fig. 2 gain, DCR, QE, and relative QE (normalized to 350 nm) for various anode pixels and wavelengths are compared as a function of the IAC for the most recent (and close to $\bar{\text{P}}$ANDA requirements) MCP-PMTs: PHOTONIS XP85112 (9002108) with one ALD-layer and a high collection efficiency (CE) and Hamamatsu R13266 (YH0250) with one ALD-layer and no film. We observe the following: there are gain fluctuations but with increasing IAC no clear trends are visible; the same applies for the DCR of both tubes. The 9002108 shows a wavelength dependent QE damage at >0.8 C/cm^2, while the YH0250 shows no aging effects until ~4 C/cm^2. The QE drop in the 9002108 can also be seen at the left PC half of the QE xy-scans shown in Fig. 3 (right), while there is no damage visible at the right half which is masked during illumination. The Hamamatsu YH0250 (left) is also half covered during illumination and does not reveal any sign of QE damage yet.

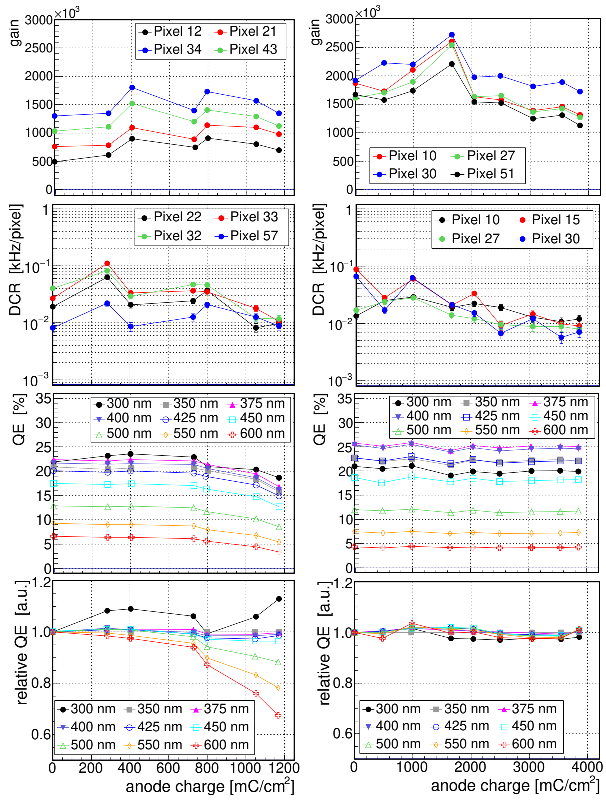

Figure 2: Gain (upper) and DCR (2^{nd} row) for different anode pixels; QE (3^{rd} row) and relative QE normalized to 350 nm (lower) for various wavelengths as function of the IAC. Shown are the most advanced MCP-PMTs with ALD coating: PHOTONIS 9002108 (left) and Hamamatsu YH0250 (right).

3. Performance of the latest MCP-PMTs

Recently both PHOTONIS and Hamamatsu have produced 2" MCP-PMTs with ALD-coating and 8×8 anode pixels which

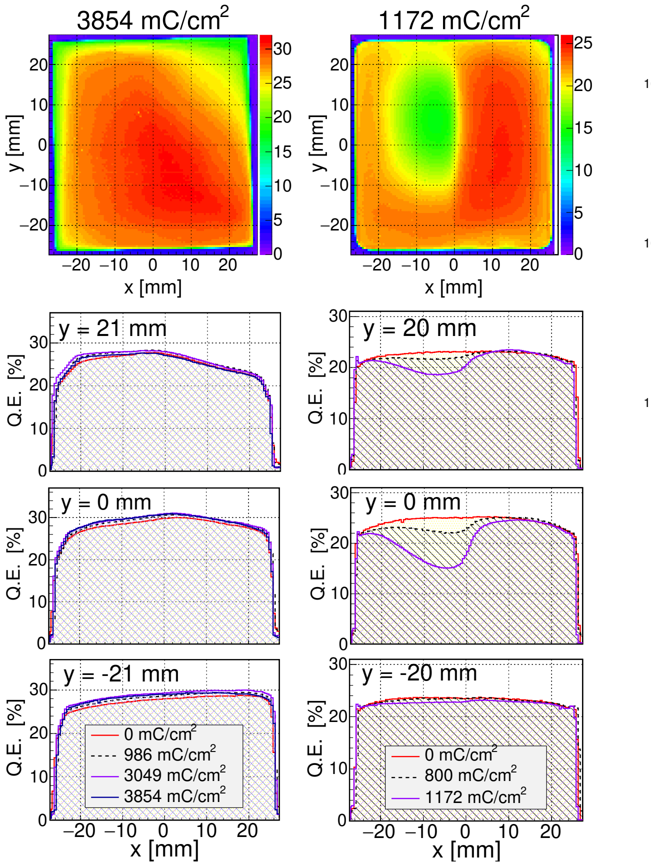

Figure 3: QE at 372 nm as a function of the PC surface for the most advanced ALD-coated MCP-PMTs. Left column: Hamamatsu R13266-M64 YH0250 (right PC half masked); right column: PHOTONIS 9002108 (left half masked). Upper row: 2d QE charts (in % [color level]); other rows: QE x-projections at different y-positions and anode charges.

are considered being very close to the performance needs of the $\bar{\text{P}}$ANDA DIRCs. Comprehensive measurements of the features of these tubes (9002108 and YH0250) were done. Most of the results were presented in detail elsewhere [14] and will not be shown here again. The overall performance of these tubes was quite good and well suitable for the $\bar{\text{P}}$ANDA DIRCs. However, it should be repeated that the gain behavior inside a B-field is different to that of non-ALD MCP-PMTs. Compared to no magnetic field the gain at 1 T drops by a factor 2 and 3, respectively, for the 9002108 and YH0250, while at an additional tilt angle of ~15° between the B-field direction and the PMT axis (perpendicular to the Chevron-plane) the gain decreases to ~30% and ~15%, respectively, of the 0 T value. The reason for this effect is still unknown.

3.1. PHOTONIS XP85112 (9002108)

The main improvements of the latest PHOTONIS XP85112 models compared to former Planacon-type MCP-PMTs are a very good rate capability of >3 MHz/cm^2 due to a lower MCP resistance and a Detective Quantum Efficieny DQE = QE*CE of almost 30% which is nearly twice the standard value. The peak QE reaches 30% from the blue to the UV wavelength region and due to a special tube design the CE is >90%. For the 9002108 the CE was measured in our lab to be ~95%, while the peak QE is about 22%. However, with another tube (XP85012 9002085 with 25 μm pores [14]) we could confirm 30% QE. Improved MCPs with a higher open aspect ratio are used to reach this CE [15]. With this design a usually lost photo electron (PE) recoiling from the MCP surface may be recaptured and traced back into an MCP pore which leads to the higher CE at one side but also to a deterioration of the intrinsic time resolution on the other side. In Fig. 4 the time distributions are shown in different views showing that at standard voltage divider settings (left) there is a long tail of recoil electrons which deteriorates in particular the RMS time resolution. These recoil electrons can arrive up to 2 ns later than the direct PEs. The overall time resolution can be significantly improved by increasing the voltage between PC and first MCP (right). This improves the RMS time resolution by a factor 2, and there is no disadvantage anymore compared to the standard CE tubes.

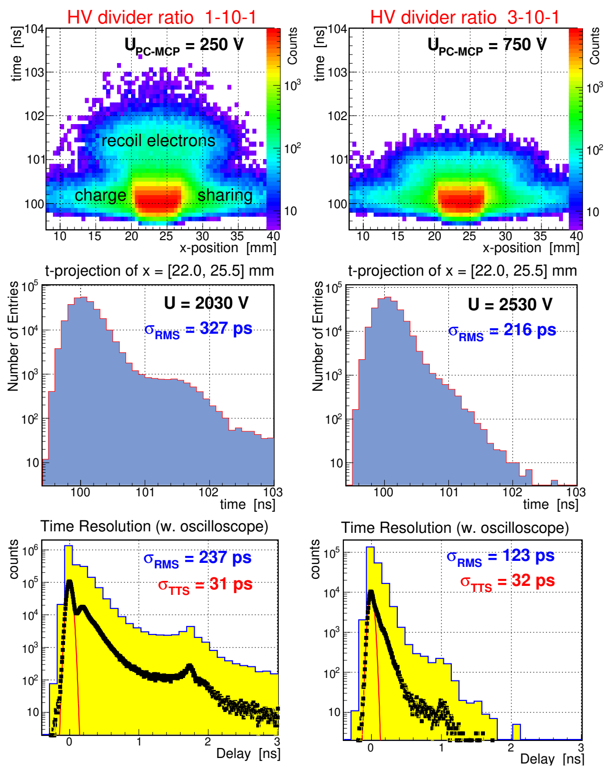

Figure 4: Time resolution and recoil electron behavior as a function of the voltage (left to right) between PC and first MCP for the new high collection efficiency (HiCE) PHOTONIS MCP-PMT 9002108. Upper row: x-t distributions showing the regions populated by recoil electrons and charge sharing crosstalk; middle row: time projection of the above data taken with a PADIWA/TRB DAQ [16, 17]; lower row: time distributions measured with an oscilloscope in high resolution mode (black dots) and in the same resolution as the above plots.

3.2. Hamamatsu R13266 (YH0250)

The main problem with the first 2" Hamamatsu MCP-PMTs with ALD-coating was a protection film in front of the first MCP to prevent feedback ions from hitting the PC. This film causes two negative side effects: a significantly reduced CE of only ~40% and a poor separation of the single photon peak

(SPP) from the noise (pedestal) in the pulse height distributions. This is demonstrated in Fig. 5 (left) for the tube JS0035. At a gain of ~10^6 and an average of ~0.25 PEs the SPP is not separated from the noise. At similar conditions the situation gets better in the new YH0250 without film as shown in Fig. 5 (middle) where the peak-to-valley ratio (PVR) is ~1.3. In addition, the neglect of a film in the YH0250 increases the CE to ~65%. An even better PVR of ~2 is observed with the latest PHOTONIS 9002108 which is shown for comparison (right).

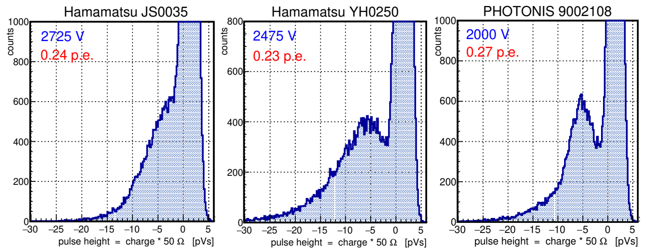

Figure 5: Pulse height distributions at ~10^6 gain and ~0.25 PEs for 2" MCP-PMTs with ALD-layer: Hamamatsu JS0035 (left) with a protection film in front of the first MCP and YH0250 (middle) without a film; PHOTONIS 9002108 (right) also without film.

3.3. Photek A1171005

Another 2" MCP-PMT with ALD-coating and 15 μm pores was developed by Photek Ltd for the TORCH project [18, 19]. Recently we received a tube of this type with 8×8 anode pixels for performance tests. The measured MCP-PMT differed from the standard layout by a lower QE – it had been "overcooked" during production – and a large metal housing around the tube to keep the backplane in good contact with the anodes. Otherwise normal operation and performance was expected. As shown in Fig. 6 the tube has indeed quite favorable parameters. The signal PVR is good, the xy-homogeneity of the gain and QE distributions are comparable to the MCP-PMTs from Hamamatsu and PHOTONIS. The TTS (transit-time-spread) and RMS time resolutions are fair with the recoil electron tail being shorter than in many other MCP-PMTs due to a closer gap between PC and MCP. A very good feature is that the integral DCR of <1 kHz per PMT and the afterpulse fraction of ~0.07% at 0.5 PE threshold are really low. The rate capability shows no gain saturation up to >1 MHz/cm^2. Also the electronic crosstalk between the anode pixels is moderate and a charge cloud size of ~1.5 mm (σ) was deduced from the charge sharing crosstalk (see Fig. 6 lower right). The CE was measured at >80%. Overall the new Photek A1171005 MCP-PMT appears to be a very competitive tube if the peak QE can be increased to >20% and if the lifetime will be sufficient.

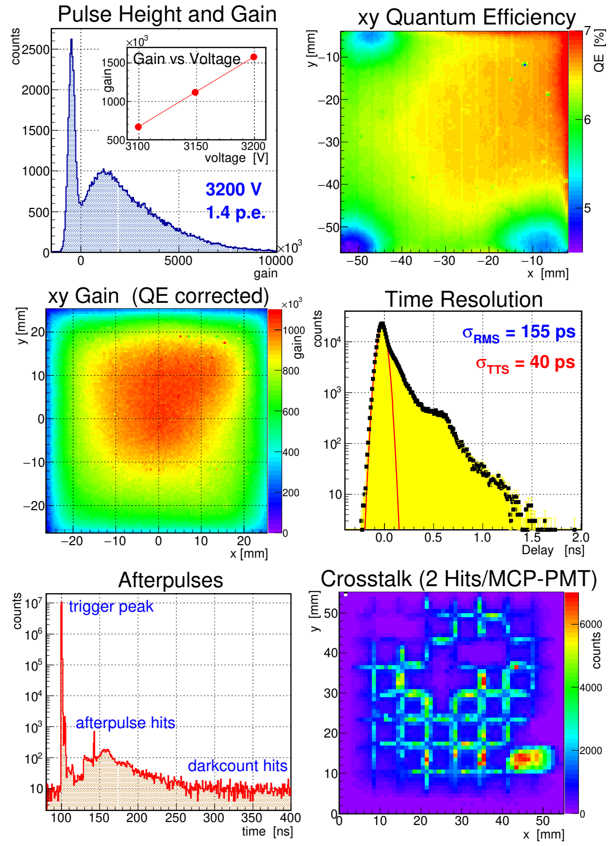

Figure 6: Performance parameters for the Photek A1171005 MCP-PMT.

4. Conclusions

The recent status of the lifetime measurements shows that there are several ALD-coated MCP-PMTs which suit well for the $\bar{\text{P}}$ANDA DIRCs. The best tube (PHOTONIS 9001393) has reached a lifetime of >22 C/cm^2 without any sign of aging. The most recent 2" MCP-PMTs from PHOTONIS (9002108) and Hamamatsu (YH0250) show significant improvements in the DQE, in particular the CE. Most other performance parameters are well suitable for $\bar{\text{P}}$ANDA. Unexpected setbacks are observed with the reduced B-field tolerance and the low lifetime of the PHOTONIS 9002108 which can hopefully be corrected in the production chain of the next tubes. Also the many positive features of the new Photek A1171005 MCP-PMT make it a promising candidate for future applications.

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