

Systematic Studies of Micro-channel Plate PMTs

A. Lehmann^{a,*}, A. Britting^a, E. Cowie^b, V.Kh. Dodokhof^c, M. Düren^d, D. Dutta^e, W. Eyrich^a, K. Föhl^d, D.I. Glazier^f, A. Hayrapetyan^d, M. Hoek^b, R. Hohler^e, R. Kaiser^b, T. Keri^b, P. Koch^d, B. Kröck^d, D. Lehmann^e, J. Marton^g, O. Merle^d, R. Montgomery^b, K. Peters^e, S. Reinicke^a, G. Rosner^b, B. Roy^e, G. Schepers^e, L. Schmitt^e, C. Schwarz^e, J. Schwiening^e, B. Seitz^b, C. Sfienti^{e,1}, K. Suzuki^g, F. Uhlig^a, A.S. Vodopianov^c, D.P. Watts^f, W. Yu^d

^aPhysikalisches Institut IV, Universität Erlangen-Nürnberg, Erwin-Rommel-Straße 1, D-91058 Erlangen, Germany

^bDepartment of Physics & Astronomy, Kelvin Building, University of Glasgow, Glasgow G12 8QQ, UK

^cLaboratory of High Energies, Joint Institute for Nuclear Research, 141980 Dubna, Russia

^dII. Physikalisches Institut, University of Giessen, Giessen, Germany

^eGesellschaft für Schwerionenforschung, Darmstadt, Germany

^fSchool of Physics, University of Edinburgh, Edinburgh EH9 3JZ, UK

^gStefan Meyer Institut für subatomare Physik, Austrian Academy of Sciences, A-1090 Vienna, Austria

Abstract

DIRC Cherenkov detectors will be the main devices for π/K separation at the PANDA experiment at FAIR. Due to their advantageous properties in terms of time resolution and especially inside magnetic fields micro-channel plate photo multipliers (MCP-PMTs) are very attractive sensor candidates. In this paper we present the investigation of several types of multi-anode MCP-PMTs. The darkcount rate, the behavior inside a magnetic field of up to 2 Tesla, the time resolution, the gain homogeneity and crosstalk of multi-pixel MCP-PMTs were found to be well suitable for the PANDA requirements. Even the rate capability of the latest models from Burle-Photonis and Hamamatsu is satisfactory. Although a big step forward was accomplished with these recently available MCP-PMTs, the lifetime is still not sufficient for the photon densities expected for the PANDA DIRCs.

Keywords:

PANDA experiment, photo detectors, MCP-PMT, magnetic field, single photon, gain, time resolution, crosstalk, lifetime
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1. Introduction

The identification of charged particles in the PANDA experiment [1, 2] at the new FAIR complex at GSI, in particular the separation of pions and kaons, will be done using the DIRC (Detection of Internally Reflected Cherenkov light) principle [3]. The Cherenkov detector will consist of two separate sub-devices, a barrel DIRC surrounding the target and an endcap disc DIRC in the forward direction, together covering a polar angle range of 5 to 140 degrees and all azimuthal angles. More details about the PANDA DIRC detectors can be found in Refs. [4, 5, 6, 7].

Due to the compactness of the PANDA detector the image planes of both DIRCs have to be placed inside the solenoidal magnetic field of up to 2 Tesla. This requires photon sensors immune to the strong field and with a high degree of pixelation to allow the reconstruction of the Cherenkov angles with sufficient resolution. The time resolution of the sensors should be <100 ps to enable the correction of chromatic dispersion effects in the radiator bars [4] and to implement the time-of-propagation version of the endcap disc DIRC [7]. Moreover, the proton-antiproton average annihilation rate of up to 20 MHz

in the PANDA experiment will lead to densities of single photons at the DIRC image planes in the order of several MHz/cm². This will put very serious constraints on any used photon sensor in terms of rate capability and lifetime.

Currently, there is no ideal sensor fulfilling all these requirements. This paper will deal with the most appealing devices to be used for the PANDA DIRCs: multi-anode micro-channel plate photo multipliers (MCP-PMTs).

2. Setup

We have investigated the properties of several types of MCP-PMTs: a circular-shaped single anode tube of the Budker Institute of Nuclear Physics (BINP) in Novosibirsk, four quadratic-shaped 8×8 pixel Planacon MCP-PMTs with different layouts of Burle-Photonis, and the recently developed linear array R10754-00-L4 with four strips of Hamamatsu. Some of the technical characteristics of these sensors are listed in Table 1. In this paper we will focus on the characteristics of the XP85012 with surface treatment and improved vacuum for an increased lifetime and on the R10754.

The sensors were illuminated with a PiLas¹ laser which produces fast light pulses of 14 ps width (σ) at a wavelength of

*Corresponding author

Email address: lehmann@physik.uni-erlangen.de (A. Lehmann)

¹Current address: INFN Sezione di Catania, Italy

¹The PiLas laser diode was delivered by Advanced Laser Diode Systems GmbH, D-12489 Berlin, Germany

372 nm; its maximum repetition rate is 1 MHz. The light is guided through a system of glass fibers, attenuated to the single photon level by neutral density filters and then focused onto the surface of the MCP-PMT with a system of micro lenses, which allows light spots from a few hundred μm to several cm diameter. With the smallest spot size and an XY-scanner the gain and crosstalk behavior of the multi-pixel MCP-PMTs were investigated as a function of the surface in steps of about 0.5 mm. For measurements of the rate capability typically a large laser spot was used.

Measurements of gain and time resolution as a function of the magnitude and the direction of a magnetic field were taken at a dipole magnet at the Forschungszentrum Julich in Germany, which delivers a homogeneous field of up to 2.2 Tesla over a pole shoe gap of 6 cm height. Usually the MCP signals were passively split after a 200-fold amplifier (Ortec FTA820A, 350 MHz bandwidth). One signal was directly fed into an ADC, while the other was discriminated (Philips Scientific 705) to determine the time delay between the MCP anode signal and the reference signal of the laser control unit. A CAMAC data acquisition system was used to record the anode charge and the time delay for the signals of each pixel.

The most precise time resolution measurements were made with a LeCroy WavePro7300A with 3 GHz bandwidth and 20 Gs/s sampling rate. This oscilloscope allows the determination of time resolutions at the few pico-second level.

For the lifetime measurements the MCP-PMTs were continuously illuminated with a 460 nm LED at a rate of 270 kHz, which is roughly the expected single photon rate at the image plane of the barrel DIRC. The entire photo cathode of the MCP-PMT was homogeneously illuminated with near parallel light. At the entrance window the light was attenuated to a level of ~ 1 photon/cm²: at a gain of 7×10^5 this corresponds to an integrated anode charge of ~ 3.5 mC/cm²/day. The stability of the LED was controlled by measuring the current of a photo diode placed close to the PMT. The MCP-PMT's response was continuously monitored by recording the pulse height with a DAQ system at highly prescaled rate. In irregular time intervals the quantum efficiency (Q.E.) of the photo cathode was determined over a 300-800 nm wavelength band. The setup for the Q.E. measurements [8] consisted of a stable halogen lamp, a monochromator with 1 nm resolution and a calibrated reference diode (Hamamatsu S6337-01).

3. Results

3.1. Dark Count

Each charged track will create a few hundred Cherenkov photons. After many reflections and other losses along the radiators and taking into account the Q.E. of the photo sensors only several tens of these photons will actually be detected. Therefore it is important to use sensors with a moderately low dark count rate. From our measurements we find that at a gain of 10^6 the typical dark count rate for most of the tested MCP-PMTs is ~ 5 kHz/cm². Only the Hamamatsu R10754-00-L4 shows a significantly lower rate of ~ 100 Hz/cm². These numbers are well sufficient for both PANDA DIRCs.

3.2. Gain inside Magnetic Field

The gain of the investigated MCP-PMTs was measured as a function of the magnitude of the magnetic field. Usually the gain reaches a maximum at ~ 0.5 Tesla and drops at higher fields. At a pore size of 25 μm the gain totally collapses just above 1 T which can be attributed to the Larmor radius of the avalanche electrons at this field. Therefore, to efficiently detect single photons up to 2 T as required in PANDA a pore size of ≤ 10 μm is needed [9].

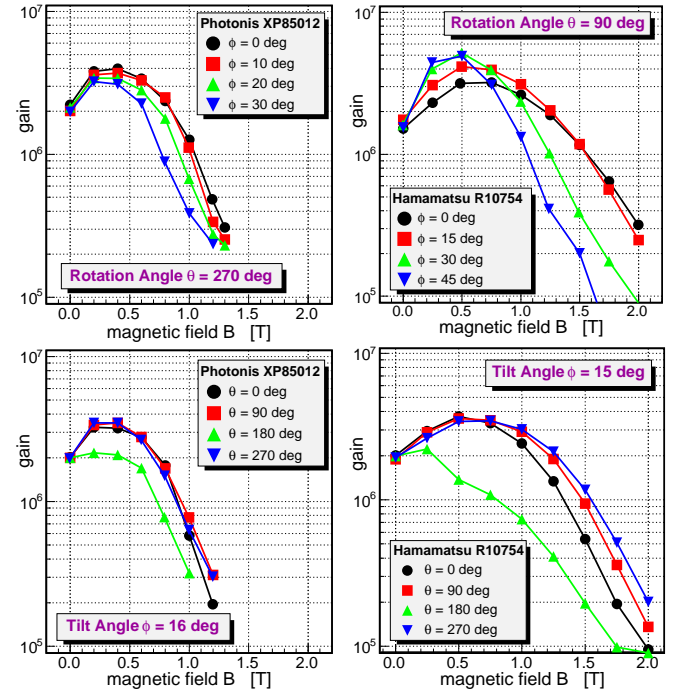


Figure 1: Gain as a function of the magnetic field direction for the Burle-Photonis XP85012 (left column) and the Hamamatsu R10754-00-L5 (right column). In the upper row the dependence on the tilt angle ϕ is shown, in the lower row that on the rotation angle θ .

For the BINP MCP-PMT (see [9]), the Burle-Photonis XP85012, and the Hamamatsu R10754-00-L4 measurements of the gain dependent on the orientation of the PMT axis with respect to the field direction were also performed. The results for the two latter devices are displayed in fig. 1. In the upper row the gain dependence on the tilt angle ϕ between the PMT axis and the field direction is shown: this demonstrates that up to $\phi \approx 20^\circ$ no significant gain change is observed, while at larger angles the gain at higher field values starts to drop rapidly. Still, even at moderate tilt angles MCP-PMTs can be used for an efficient single photon detection in high magnetic fields. This is an enormous advantage compared to standard dynode-based PMTs.

In the lower row the gain behavior at different rotation angles θ of the PMT around the field axis and at $\phi \approx 15^\circ$ is shown: there is a significantly different slope at $\theta = 180^\circ$, when the capillaries of one of the two MCP layers point exactly along the field direction. At all other measured rotation angles the gain follows roughly the same slope.

Table 1: Characteristics of the investigated MCP-PMTs

	BINP	Burle-Photonis				Hamamatsu
		Prototype	XP85011	XP85013	XP85012	
pore diameter (μm)	6	10	25	25	25	10
number of pixels	1	8×8				1×4
active area (mm^2)	$9^2 \pi$	51×51		53×53		22×22
total area (mm^2)	$15.5^2 \pi$	69.5×69.5	71×71	59×59		27.5×27.5
geom. efficiency (%)	36	54	52	81	81	61
photo cathode	multi-alkali	bi-alkali				multi-alkali
comments	~5 nm Al_2O_3 protection film					improved vacuum protection film planned

3.3. Time Resolution

The distribution of the measured time resolutions [9, 10] consists of a narrow peak (σ_t) and a tail to one side which originates from photo electrons backscattering at the MCP entrance. This behavior was seen for all investigated MCP-PMTs. As listed in Table 2 the width of the peak was always ≤ 50 ps, with the best resolution of 27 ps (at 10^6 gain and after x200 amplification of the MCP anode signal) for the BINP MCP-PMT with 6 μm pore diameter. All given time resolutions are without any correction for the resolutions of the used electronics modules and the laser pulse width.

Table 2: Single photon time resolutions of the investigated MCP-PMTs

manufacturer	type	pores (μm)	σ_t (ps)
BINP	#73	6	27
Burle-Photonis	Prototype	10	41
	XP85011	25	49
	XP85013	25	51
Hamamatsu	R10754-00-L4	10	32

The time resolutions were also measured as a function of the magnitude of the magnetic field, with no significant deterioration at higher fields being observed.

3.4. Gain Homogeneity and Crosstalk

The response of the multi-anode MCP-PMTs was investigated with XY-scans across the active surface. The gain of the different pixels in a device can vary by a factor 7 as in the Burle-Photonis prototype [10]. The 25 μm pore MCP-PMTs of the latter manufacturer show typical gain variations up to a factor 2 across the 64 pixels, as plotted in fig. 2 (upper left) for the XP85012. The lowest gains are usually observed for the edge pixels and especially at the corners. The Hamamatsu R10754-00-L4 even shows significant gain inhomogeneities within one pad (fig. 2, lower left), with measured fluctuations sometimes exceeding a factor 2.

A lower gain may cause a reduced detection efficiency of the pixel. In fig 2 (right column) the number of counts of each pixel in a row is shown, when the active surface of the MCP-PMT was illuminated in steps of 0.5 mm along the x-coordinate (or column) while the y-position (or row) was kept constant.

These plots also show the crosstalk among the anode pixels. For the Burle-Photonis XP85012 crosstalk is mainly visible at the transition to the adjacent pixels, most likely caused by charge sharing at the anode and by backscattered photo electrons at the MCP entrance, while pixels further away are hardly affected. In contrast, for the Hamamatsu R10754-00-L4 a significant response of all other pixels is observed when a certain pad is illuminated; even pixels far from the light spot can fire. Further investigations with the latter MCP-PMT showed that most of the crosstalk is of electronic nature and can be eliminated to a large extent by a modified construction of the tube: the second MCP layer is split into separate sectors each of the size of the adjacent anode pad [11].

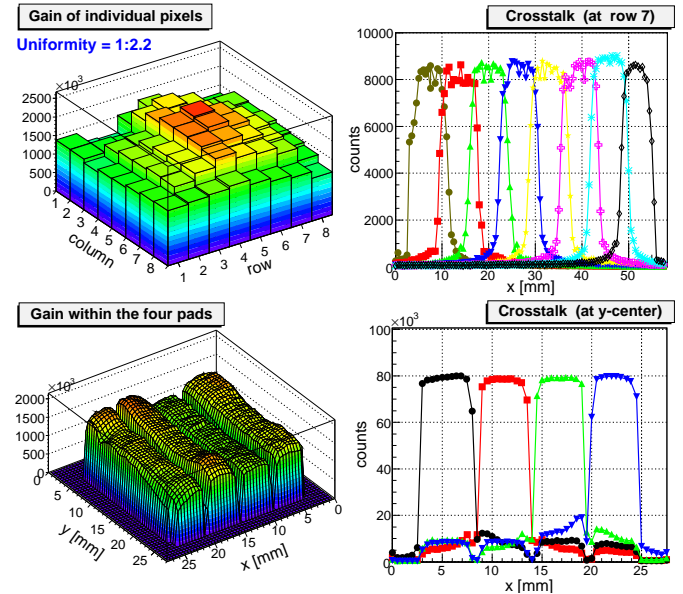


Figure 2: Gain (left) and crosstalk behavior along one row of pixels (right) for the Burle-Photonis XP85012 (upper) and the Hamamatsu R10754-00-L4 (lower).

3.5. Gain Stability at High Rates

The rate capability of MCP-PMTs is one of the most critical issues in high rate experiments like PANDA. The expected photon density at the readout (anode) plane (after Q.E.) is ~ 200

kHz/cm² for the barrel DIRC and up to 2 MHz/cm² for the endcap disc DIRC. At such photon rates the current in the resistive material of the MCP capillaries may not flow off fast enough, which causes charge saturation effects. The result of this is a rapidly decreasing gain as seen in fig. 3 where the normalized gain is plotted versus the anode current. Assuming a certain gain of the tube (e.g., 10⁶ in the figure) this current can be translated into a single photon density which is given at the upper axis.

The gain of most of the studied MCP-PMTs starts dropping already at photon densities well below 1 MHz/cm². However, practically no gain loss up to ~2 MHz/cm² single photons is observed for the Burle-Photonis XP85012, and the Hamamatsu R10754-00-L4 is even capable of standing rates >5 MHz/cm² without the gain getting lower. The rate capability of these models would be sufficient for both PANDA DIRCs, with the R10754 being the preferred choice for the endcap disc DIRC.

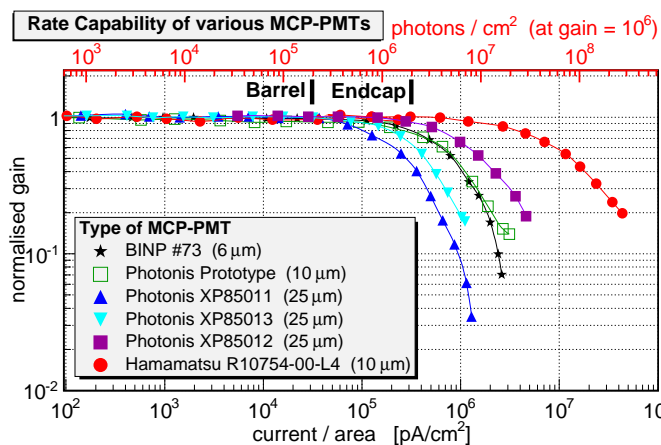


Figure 3: Rate capability of various models of MCP-PMTs: the relative gain is plotted versus the anode current. At the upper axis the translation into a rate for single photons assuming a constant gain of 10⁶ is given. The expected rates (after Q.E.) for the barrel DIRC and the endcap disc DIRC are also indicated.

3.6. Lifetime

The expected photon rates at the PANDA DIRC's readout planes accumulate to an integrated anode charge of ~1 C/cm²/y for the barrel DIRC and, dependent on the layout, up to 10 C/cm²/y for the endcap disc DIRC, assuming a PMT gain of 10⁶ and continuous data taking. Up to recently these conditions were beyond the reach of any commercially available MCP-PMT. However, in the latest generation of MCP-PMTs these limitations are tried to overcome by following two different approaches. Burle-Photonis applies a special surface treatment to the MCPs and significantly improves the vacuum inside the tubes. Hamamatsu and BINP are putting thin protection foils at the first MCP layer to stop the feedback ions from reaching the photo cathode. This protection film can principally also be put at the second MCP layer with the advantage of not reducing the collection efficiency of the MCP-PMT.

Our first lifetime measurements were done with a BINP single anode tube and a Burle-Photonis XP85012. In both tubes

the gain remained almost constant over the whole illumination period of ~2 months. However, the Q.E. had dropped by more than 30% after an accumulated anode charge of 80 mC/cm² or 110 mC/cm², respectively. From the slopes in fig. 4 it is also obvious, that the rapidity of this drop in Q.E. depends on the wavelength of the incident photons. The effect is much less pronounced at shorter wavelengths, especially in the UV-region.

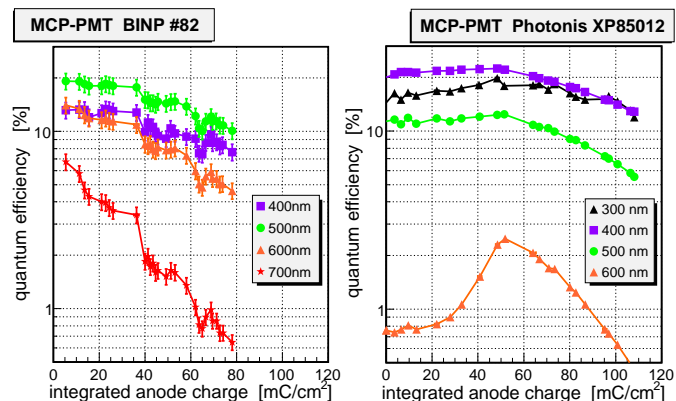


Figure 4: Quantum efficiency as a function of the integrated anode charge. The BINP PMT was equipped with an aluminum-oxide film at the entrance of the first MCP layer. The Burle-Photonis XP85012 had an improved vacuum.

4. Conclusions

Both the new Burle-Photonis XP85012 and the Hamamatsu R10754-00-L4 MCP-PMTs are promising sensor candidates for the PANDA barrel DIRC and the endcap disc DIRC, respectively. They fulfill all boundary conditions except the lifetime requirement. Further improvements are necessary in this direction, in particular a protection foil in the R10754-00-L4 which seems already existent now [12]. A 10 μm pore version of the Burle-Photonis MCP-PMT is also available meanwhile which will improve its immunity to magnetic fields above 1 Tesla. Its lifetime still needs to be tested.

In summary, the latest improvements of the two most serious issues of MCP-PMTs, the rate capability and the lifetime, give us confidence that these devices are still serious contenders for the sensors of the PANDA DIRCs. The optimum scenario for another significant enhancement of the lifetime would be a combination of the treated MCP surfaces, the better vacuum inside the tube and a protection film at the second MCP layer.

Acknowledgements

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