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# PMT Characterization for MAGIC II Telescope

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**Abstract:** MAGIC, a 17m diameter Cherenkov telescope located on the Canary Island of La Palma, is the biggest IACT (Imaging Atmospheric Cherenkov Telescope) in the world. For lowering the energy threshold and improving the sensitivity, the MAGIC collaboration is currently building a second telescope (MAGIC II), using Photomultipliers(PMTs) with a better sensitivity. Various measurements of different characteristics of PMTs, such as single photoelectron spectrum(SPE), afterpulse, aging and photoelectron detection were performed. The results from selected PMT candidates of different companies will be presented here.

## Introduction

The MAGIC telescope has been in scientific operation since the summer of 2004. Currently, it is the largest ground-based gamma ray telescope in the world. The main purpose of the MAGIC I design was to study high energy phenomena in the universe in the unexplored energy range down to 30 GeV. For improving the sensitivity further and also benefitting from the stereoscopic/coincidence operational mode, we are building a second telescope, MAGIC II [1], at about 85 meters' distance from the MAGIC-I telescope. The imaging camera will be equipped with high quantum efficiency (QE) photomultiplier (PMTs) and also Hybrid photodiodes (HPDs). The signals will be read out by a fast sampling system of 2 GSamples/s in order to reduce the background photons coming from the night sky and to achieve a better gamma/hadron separation by taking into account the timing profile of the Cherenkov light. Our goal is to lower the threshold by a factor two with advanced photon detectors and a fast readout system. PMTs are very suitable photon sensors for measuring very fast and low light level signals. Though PMTs have already been widely used in high energy physics before, their characteristics may differ from tube to tube. We have searched the current market for the PMTs which fullfilled the following requirements:

- High quantum efficiency.
- Low gain ($2 * 10^4$), because of the moon observation.
- One-inch diameter and hemispherically shaped photocathode.
- Six-dynode structure for better timing characteristics.
- Low afterpulsing rate. It has been understood that lowering the trigger threshold is limited in part by the afterpulsing rate induced by single photoelectron pulses due to the night sky light. [2]
- Fast and short pulses.

To really understand each pixel, a variety of measurements were performed. The impacts on the future MAGIC II telescope will also be discussed.

## The Quantum Efficiency Measurement

The Quantum efficiency is a quantity used to express the sensitivity of a photonsensor. For fast and

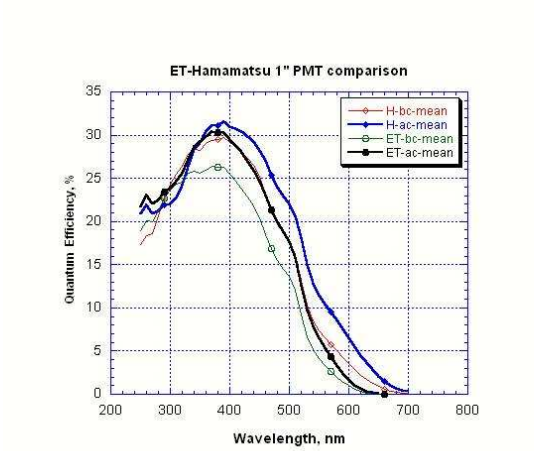


Figure 1: PMT QE curves from different companies. H-bc and H-ac stand for Hamamatsu PMTs before and after coating. ET-bc and ET-ac stand for Electron Tubes PMTs before and after coating.

low light level experiments, it becomes important to provide high signal-to-noise ratio photon sensors.

To enhance the QE, we improve it by extending the spectral sensitivity in the short-wave UV range using a wavelength shifter (WLS) and, further, by increasing the overall quantum efficiency (QE), applying a layer of structured lacquer acting as a photon scatterer [3]. In total, 20 PMTs from the companies Hamamatsu and Electron Tubes were measured.

The QE test setup included a deuterium and tungsten lamp. A spectrophotometer was used as a wavelength selector and a 10x10 mm calibrated PIN diode from Hamamatsu served as a reference. The PIN diode had a calibration precision of 2 %. The photocathode was fully illuminated and the current produced by the anode was measured. We applied a potential difference of 200V between the photocathode and the first dynode. For eliminating the gain influence, we shorted all the 6 dynodes. Every charge collected inside the PMTs would produce anode current and be measured.

In Figure 1, we plot the average QE curves of 20 coated and uncoated PMTs from different companies.

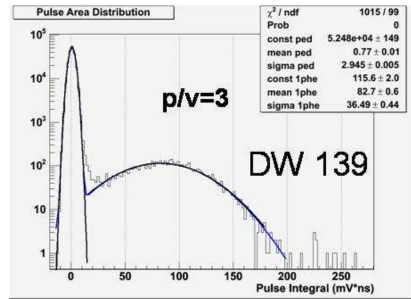


Figure 2: The SPE of PMT DW139 from Electron Tubes. The highest peak shows pedestal events,the second peak single photoelectron events. The data are fitted with two Gaussians.

## Single Photoelectron Spectrum

When a PMT is used to detect a very weak signal, the pulses from individual photoelectrons are well separated in time. Because of the secondary electron emission process in the first dynode, the single-electron pulses show very large amplitude fluctuations. We tuned the laser light density down to single photoelectron regime. The laser triggered the FADC to record the pulses from PMTs.

The single photoelectron pulses were extracted from FADC data and we integrated the charge for each pulse. The single photoelectron spectrum is shown in Figure 2. We kept the single photoelectron events smaller than 5% such that the probability to get two photoelectrons was smaller than 2% of the number of single photoelectrons.

From the SPE, we could also calculate the peak-to-valley (P/V) ratio. For the future MAGIC II telescope, we are going to reject pixels which have a P/V value lower than 1.2 .

## Time Characteristics

The time characteristics of photonsensors are quite important for IACTs. Since the Cherenkov light flash is always quite short, usually a few ns, we need fast PMTs to reduce the background. We measured the pulse response width at half of the maximum (FWHM) of the anode current pulse delivered in reponse to a very short and narrow laser light pulse (about 40 ps). The pulse width de-

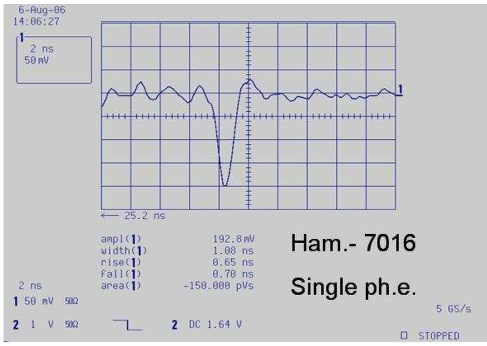


Figure 3: Single photoelectron pulse from a Hamamatsu PMT. The pulse was measured with a fast oscilloscope with $1.5$ GHz of bandwidth and a 5 G/s sampling rate.

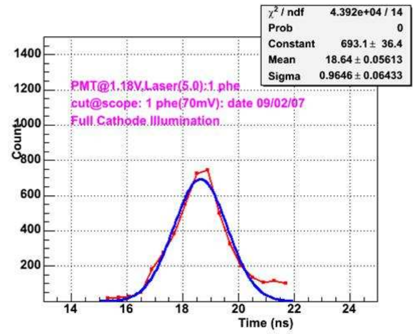


Figure 4: The transit time jitter for single photoelectron pulses from the Hamamatsu PMT. The horizontal axis is the transition time. The transit time spread (TTS) is about 960 ps. Note that TTS becomes shorter if the pulse has more photoelectrons.

pends on the light illumination level and is minimum when this level is so low that the probability of more than one photoelectron being emitted per light pulse is very small.

We measured with a 2GHz bandwidth amplifier (gain $\sim 100$) followed by a fast oscilloscope ($1.5$ GHz in bandwidth, 5 G/s sampling rate). Most of the pulses had a rising time of appr. $600 \sim 800$ ps and a falling time of $700 \sim 1000ps$. The pulse width (FWHM) was around $1 \sim 1.5ns$. In Figure 3, the single photoelectron pulse from the Hamamatsu PMT is shown.

The transit time spread (jitter) was measured, too. The transit-time fluctuation affecting the pulse response may have been caused by the initial velocity spread of electrons emitted by different electrodes or may be due to different points of emission from the same dynode. Because of the geometry of our tubes, we believe that the main reason for the difference is the cathode/first-dynode space. However, there is another important factor, i.e. the voltage applied between the electrodes. The time resolution of the tube could be defined as the FWHM of the probability distribution of this fluctuation. It is also proportional to $1/\sqrt{n}$, where $n$ is the number of photoelectrons per pulse. From the Figure 4, we see the transit time distribution when the PMT has high gain $1.12 * 10^5$. We also found that if we lowered the gain down to $7 * 10^4$, the time jitter changed very little.

## Aging Test

Exposing the PMTs to constant light intensity over a period of time will make the gain of the PMT decrease. This is important for IACTs, because the PMTs are constantly exposed to night sky background light (NSB). The gain of the PMTs drops because of the fatigue of the dynode. The lifetime of the PMT is defined as the time when the gain of the PMT drops to $50\%$. In order to speed up the measurement, all measured PMTs were illuminated by highly intense light. We tuned their gains such that they had the same initial anode current, i.e. $150\mu A$. The measurement was operated for approximately one week (10150 minutes) in total. We tested with 4 PMTs. Their lifetime was estimated to be 50 $\sim$ 60 years, assuming the NSB at La Palma to be 1 uA and $10\%$ of the duty cycle of the telescope operation.

## Afterpulsing

When the dynodes are bombarded by electrons, during the amplification process, some residual molecules which are resting on the surface of the dynode will be ionized and the positive ions will have the chance to fly back to the cathode. This

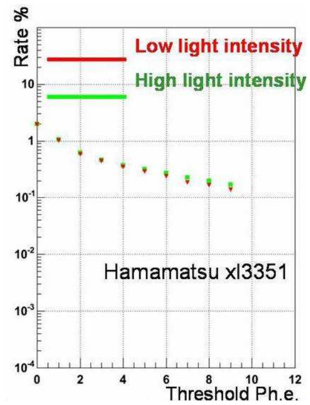


Figure 5: The afterpulse rate for the Hamamatsu xc3351 PMT at different photoelectron thresholds.

process is the so-called afterpulse. We used a pulsed laser (wavelength 405 nm) as our light source and triggered the FADC externally. Once the FADC was triggered, there was a main pulse of about several tens of photoelectron coming from the laser and we searched for the afterpulses within the following 2 $\mu s$. Within this period, we applied different thresholds and then counted the number of afterpulses and normalized this number to the total number of main pulses and the number of photoelectrons in these main pulses. To check if the measurement depended on the intensity of the laser pulse, we measured the PMTs with two different intensities. In Figure 5 the different afterpulsing rates of Hamamatsu PMTs at different intensities are presented. All measured PMTs had an afterpulsing rate of about 0.2 % to 0.8 %.

## Photon Detection Efficiency

In the above QE measurement, we measured all the photoelectrons emitted from the photocathode. Under normal operation, some of the photoelectrons are collected at the first dynode and they do not contribute to the amplified signal. The total photon detection efficiency is the ratio of the photoelectrons contributing to a measurable signal at the anode to that of all photoelectrons produced at the photocathode.

We measured two PMTs simultaneously, using the same diffuse light source with symmetric geometry in order to have a direct comparison of the photon detection efficiency of the two sensors. Afterwards, two PMTs were swapped in order to get rid of the small asymmetry of the illumination. Then we evaluated relative efficiencies by numbers of detected single photoelectrons. We found the photoelectron efficiency of the Hamamatsu PMTs to be high enough.

## Conclusion

We set up procedures to measure the different properties of a sample of PMTs. For MAGIC II we selected Hamamatsu PMTs. The company Hamamatsu will deliver PMT modules which include a socket with a Cockcroft-Walton type High Voltage generator. The PMT socket and all the front-end analog electronics is assembled to form a compact pixel module. All will be embedded in the camera pixel cluster design. [1].

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