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High detection efficiency MCP-PMTs with single photon counting capability for LIDAR applications

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ABSTRACT

In this paper the focus is on the implementation of Photonis MCP-PMTs with single photon counting capability for LIDAR applications. In particular we are presenting our MCP-PMTs based on HI-QE photocathodes optimized for different spectral ranges (UV, Blue, Green with typical QE>30%) and for fixed laser wavelength of 355 nm and 532 nm [1]. In addition to the high QE, those photocathodes demonstrate low dark rates, typically below 50 Hz/cm^2, property that is important for low-rate signal detection. The collection efficiency of the MCP is also improved to reach almost 100%, allowing to increase the detective QE by a factor of 1.5 compared to conventional MCP-PMTs [2]. The timing performance for MCP-PMTs operated at low and high rate photon fluxes are also studied. Non-linearity effects for high rate of illumination are analyzed and MCP-PMTs with extended linearity are presented. All these improved detection properties can be combined with the possibility of fast triggering and extended life time technology making these devices unique for future atmospheric and altimetry LIDAR missions.

Keywords: MCP-PMT, LIDAR, QE, linearity, lifetime, dark rate

1. INTRODUCTION

Space programs based on LIDAR instrumentations, recording altitude dependent laser scattered signal from the atmosphere, ocean and ground, require state-of-the-art detectors [3]. A typical detection time window for a single laser pulse is a few 100 µs with a repetition rate of a few 100 Hz. In order to reach the required vertical resolution, the pulse laser duration and detector resolution have to be matched to about 10 ns. The detectors also have to be tuned for the typical laser wavelength used for space LIDAR applications: 355 nm, 532 nm and 1064 nm. The dynamic range required is ranging from single photon counting in the cases of weak reflection signal in the high atmospheric layers or from below the ocean surface to up to few hundred thousand photons within the 10 ns window for the case of ground, ocean or arctic surfaces. The detectors should demonstrate quick recovery time after the overshoot or even ideally still have to be in linear (non-saturation) regime, so that recording the amplitude of the signal can directly be linked to the number of photons in the reflection peak. In addition, the detectors should demonstrate high longtime stability, keeping in mind mission durations of about 5 to 10 years.

A MCP-PMT is a vacuum device consisting of a photocathode, absorbing the light and emitting photoelectrons, typically two MCPs, multiplying the electrons from the photocathode by a factor of about 10^5 -10^6 and an anode that can be single or segmented, to collect the output bunches of electrons. The time resolution of these devices is in the ns or even sub-ns range with a rise time and time transfer spread being below 200 ps and 40 ps (σ), respectively. The Detective Quantum Efficiency (DQE) is mostly defined by the photocathode QE and by the Collection Efficiency (CE) of the MCPs [2]. For high flux illumination the output linearity is an important parameter and is typically limited by the MCPs. Indeed when a large current is extracted to the anode it depletes the MCP and requires time for recovering.

In this paper we discuss the MCP-PMT performances in perspective to potential LIDAR application requirements. In chapter 2, we first present the devices used and experimental methods of characterization. The results obtained are discussed in chapter 3, where section 3.1 is focusing on detection parameters such as QE spectra, MCP collection efficiency, dark rate and lifetime, section 3.2 and 3.3 are presenting the behavior of the MCP-PMTs at low and high photon flux detection conditions.

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2. EXPERIMENTAL

The measurements are done with Photonis MCP-PMTs. The chosen configuration is an 18 mm MCP-PMT with a S-20 Hi-QE photocathode, a dual 6 µm pore one inch MCP with Hi-CE technology, and a single anode. The Open Area Ratio (OAR) of the MCPs is specified to be above 65%.

To measure the QE in the spectral range of 200 nm – 900 nm, the photocathode is illuminated by monochromatic light using Omni-λ300 Grating Monochromator (2.5 nm resolution) equipped with a deuterium/halogen light source. A 200 V bias voltage is applied to the MCP and the current from the photocathode (1 nA typical values) is detected using a low-noise amplifier. The intensity of the light from the monochromator is measured with a calibrated Si-photodiode.

The MCP gain is derived from the mean energy of the Pulse Height Distribution spectrum, where the measurements are done at a low level of illumination corresponding to a single photoelectron event [1]. The PHD spectra is recorded using a Charge Sensitive Preamplifier CSP10 (1.4 V/pC), a shaping amplifier CSA4, and a multi-channel analyser MCA3 [4].

To measure the collection efficiency of the MCPs, the PHD data are used. The rate of the incoming flux of electrons to the MCP is adjusted to provide an input rate in the range of 50-100 kHz while at the same time, the rate of the output pulses at the anode is measured using the PHD setup. The ratio of the input and output rates provides directly the value of the CE coefficient [2].

For lifetime measurements the gain of the MCP is adjusted, by tuning the MCP bias voltage, to a nominal value of about 10^5 which is found to be the optimal value with respect to readout noise, saturation and lifetime. The photocathode surface is homogeneously illuminated by a 400 nm LED source and the light intensity is adjusted in such a way that the anode current is about 5% of the MCP strip current, ensuring an operation of the MCP-PMT in linear mode. The output anode current and LED intensity are measured in parallel and continuously while the photocathode current is recorded point wise. These measurements allow to derive long-term stability of the tube, namely photocathode QE and MCP gain.

For the timing and linearity characterization, a multiple-event time digitizer with a 100 ps time bin resolution (Model MCA6 [5]) is used to record the electron bunches arriving to the anode. To derive the MCP-PMT time performance at high density illumination fluxes, a LED source with neutral density filters and an 80 MHz 405 nm laser with 100 ps pulse width are used. The output linearity measurements are done in dc-mode and in counting mode by controllably increasing the LED intensity and recording the anode current or counting the anode pulses.

3. RESULTS AND DISCUSSIONS

3.1 Quantum efficiency spectra, MCP collection efficiency, dark rates and lifetime

Figure 1 shows the QE spectra for transmission mode S-20 based Hi-QE series photocathodes over the 200-900 nm spectral range. The new photocathodes are developed to target specific spectral ranges which are here called Hi-QE Blue, Hi-QE Aqua and Hi-QE Green [1]. These photocathodes exhibit much higher QE values than the conventional S-20, clearly exceeding 30% as seen in Figure 1.

Hi-QE Blue photocathodes are designed to provide the highest QE in the 260-400 nm spectral range. The QE spectrum shows a broad plateau in this range, again with a typical QE above 30% and a max QE of about 35% around 355 nm. Hi-QE Aqua photocathodes are targeting to have maximum quantum efficiency at 400 nm. In the present case (see Fig.1) the QE at 400 nm is close to 35% (compare to 30% for Hi-QE Blue). Additional feature of this cathode is a relatively narrow bandwidth that allows filtering the background spectra away from the central line. Hi-QE Green photocathodes demonstrate QE values above 30% in the range of 380-480 nm. While at 532 nm the QE is already on the decreasing slope, it is still around 17%. Compared to the other Hi-QE photocathodes, the sensitivity of the Hi-QE-green is much higher at longer wavelengths up to 700 nm.

The Hi-QE photocathodes exhibit all a very low dark rate, below typically 50 Hz/cm^2 [1]. In particular the Hi-QE Green is in that sense remarkable as it combines a good QE at 532 nm with the low dark rate property, making the Hi-QE Green a unique photocathode for photon counting in this spectral range. Further work is also in progress to specifically boost the QE at 532 nm for laser applications.

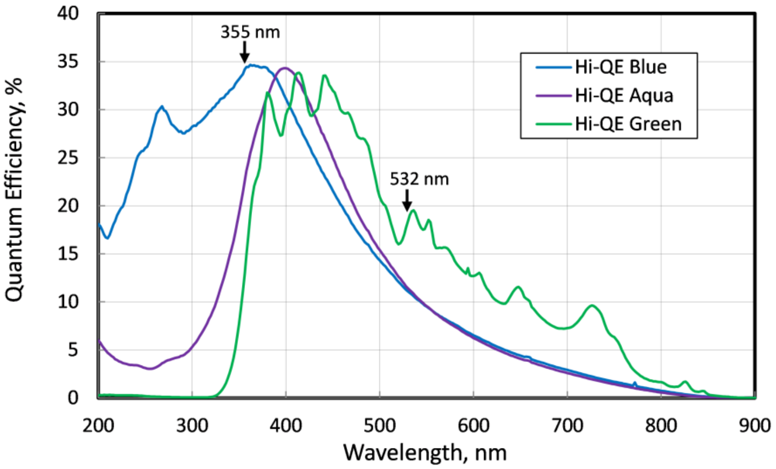

Figure 1. Quantum efficiency spectra for developed Hi-QE S-20 photocathodes: Hi-QE Blue (blue), Hi-QE Aqua (purple) and Hi-QE Green (green). Arrows show the positions of 355 nm and 532 nm laser lines.

The collection efficiency of the MCP is also a key parameter which directly impacts the detective quantum efficiency of the MCP-PMTs. We have shown [2] that the collection efficiency of standard MCPs with conventional electroding is close to the OAR of the MCPs, that is about 65% for 6 µm MCPs. Thus, almost all photoelectrons entering the web of the MCP are lost. In the case of Hi-CE MCPs, the situation is drastically improved; indeed close to 100% of the photoelectrons arriving at the MCP stage generate pulses on the anode.

The benefit of the Hi-CE MCPs, compared to conventional MCPs, is almost a factor 1.5 increase of the DQE of the detector. However, due to counting of electrons scattered from the MCP top surface (which are mostly lost for conventional MCPs) the timing characteristic of the Hi-CE MCPs is slightly degraded with respect of conventional MCPs but when no picosecond resolution is required (that is mostly the case for LIDAR applications), the implementation of Hi-CE MCPs is hugely beneficial as it improves the detection efficiency of the MCP-PMT.

The lifetime of MCP-PMTs is in most cases limited by the degradation of the photocathode by ion feedback. Primary photoelectrons go to the MCP channel, hitting the walls and generating secondary electrons; this process is repeated multiple times within the MCP channel, resulting in a final gain of 10^5-10^6. But during the process also positive ions can be freed from the walls due to electron stimulated desorption and part of them drifts back to the photocathode. Those ions bombarding the photocathode damage the thin emission layer resulting in QE degradation and at the same time also generate after-pulses. Both of these effects, in first approximation, are proportional to the MCP gain.

Thanks to the fact that the Hi-QE photocathodes are based on state-of-the-art S-20 technology, they are more resistant to this degradation mechanism than for example S-25 or III-V based photocathodes, resulting in a longer lifetime. However, for space missions with expected 5-10 years of operation and with possible high load of coming photons, the operational stability has to be studied in more details.

Our preliminary lifetime results, shown on Figure 2, are obtained with a Hi-QE Blue MCP-PMT at nominal MCP gain of 10^5. The LED-intensity is adjusted to provide 0.5 µA of dc anode current at the beginning of the lifetime test, chosen to be just below the saturation point. For this measurement the MCP voltage and the light intensity are fixed and the anode current is monitored over the time. Along with this measurements the photoemission current from the photocathode is regularly measured allowing to monitor the variation of the MCP gain and the photocathode QE independently.

This specific lifetime test has been running for 5 months. On one hand the gain shows a small variation within 15% of the start value appearing at the beginning of the test, though it is not critical for photon counting mode measurements, we can expect to be able to reduce this variation. On the other hand the QE has dropped down to about 70% of its original value at 6.5 C extracted charge on the total area. Extrapolating those results, the expected lifetime (defined as a QE drop of 50%) will be about 9 C (corresponding to 3.5 C/cm^2).

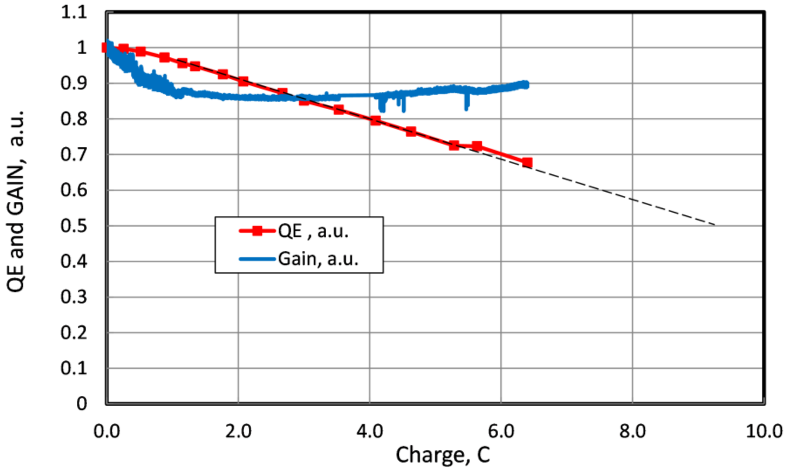

Figure 2. Relative change of quantum efficiency at 400 nm and gain vs total charge extracted from the anode, with extrapolated lifetime of 9 C for 50% QE drop.

Assuming a continuous 10 MHz photon flux to the detector, DQE of 30%, and nominal MCP gain of 10^5, the lifetime of the detector can be estimated to be about 6 years. Potentially, the use of triggering option of the MCP-PMT will allow to reduce drastically the contribution of the background during daytime operation on the total load, extending the lifetime of the device. For space grade detectors being under development we expect to improve the intrinsic lifetime of S-20 Hi-QE MCP-PMTs by a factor of 2-3. This long lifetime MCP technology is being tested on the Planacon™, another MCP-PMT device from Photonis, though the conditions of use are different the results presented in [6] are very promising.

3.2 High rate detection capability within short time intervals

In this chapter and chapter 3.3 we consider the performances and limitations of MCP-PMT detectors in high illumination conditions. First, the case of fast counting rate in a short period is described, when the average output current/rate is staying below the saturation level, then the case of longer detection window or continuous mode operation, when the detector faces saturation problem.

When it is required to count photons only within a defined short time interval (that can be the case for LIDAR applications with the reflection of the light from highly reflecting surfaces), the single anode MCP-PMT detectors are capable to measure very high count rates. In this case the maximum rate is limited by the time resolution of the detector, and the capability of the read-out electronics.

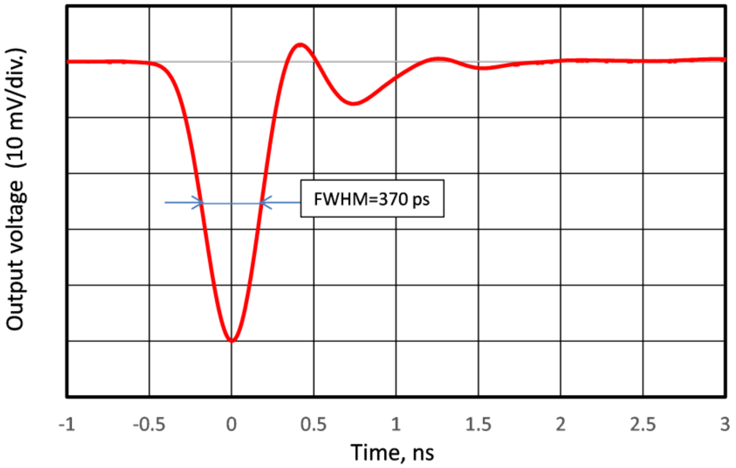

Figure 3. Time response waveform of Photonis fast MCP-PMT measured with 2 GHz 40 dB preamplifier and 2.5 GHz oscilloscope.

The timing performance of the MCP-PMT for single photoelectron response is demonstrated on Fig.3 for a Photonis fast MCP-PMT detector. The time response waveform is recorded with a 2 GHz 40 dB preamplifier and a 2.5 GHz oscilloscope. The rise time of the pulses is found to be below 200 ps with a full width half maximum to be about 350 ps. This excellent time resolution allows to resolve series of pulses separated by about 1 ns; that corresponds to 1 GHz count rate capability within a short time window.

When the limitation of the measurements is the time resolution of the detector and not the saturation (so we are still discussing low average load of photons) it is possible to extend the detection range to higher rates. One of the possibilities is to use a multi anode configuration with separated read-out electronics for each channel, that will scale the rate with the amount of channels. Another way is to measure the amplitude of the arriving photoelectron pulses by fast ADCs electronics. To make possible the counting and the fast ADC detection chains to work in parallel, the two detector’s outputs have to be settled directly from the detector. However, we have to make clear that GHz detection rates are possible only within short time window. For high rate and continuous mode operation the MCP-PMT will be saturated. The behavior of MCP-PMT detectors at these conditions will be discussed below.

3.3 Detection capability for high-rate continuous illumination

For continuous high flux of photons the maximum detection count rate is typically much below the rate in short time illumination discussed above, it is limited by the saturation of the MCP. The current extracted from the MCP, which is proportional to the MCP gain and photon rate, has to be recovered by the strip current flowing through the channel wall, the latter being typically 10 µA. When the extracted current becomes higher than 5% of the MCP strip current (scaled approximately to the area of illumination) the saturation takes place.

Figure 4 demonstrates the saturation effect for DC and for photon counting measurements of a conventional MCP-PMT with nominal settings corresponding to an MCP gain of about 10^5. A LED source is used for these measurements (8 mm diameter spot illumination) with intensity reduced by neutral density filters down to single photoelectron level. The anode current (red curve on Fig.4) and then the pulse count rate (blue curve) are measured while changing the number of incident photons. At low light intensities the anode current (dc-mode) linearly follows the increase of light intensity (black curve) but at higher illumination level the anode current starts to deflect from the linear behavior. For this case, the MCP-PMT stays within 90% and 50% linearity up to about 0.1 µA/cm^2 and 0.5 µA/cm^2, respectively.

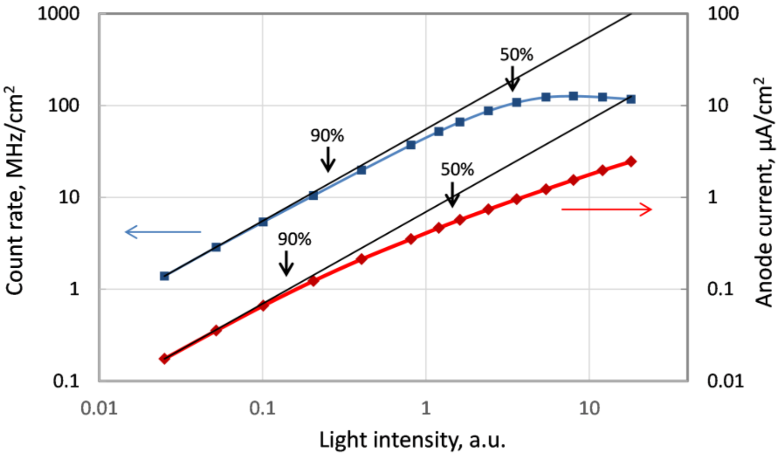

Figure 4. Averaged detector count rate (blue) and anode dc-current (red) as a function of continuous light intensity (for 8 mm diameter illumination spot). The black lines are calculated curves corresponding to the theoretical linear behavior. The vertical arrows show the light intensities where experimental curves are within 90% and 50% of the linear output.

For the photon counting measurements (blue curve, Fig.4) the saturation effect is also observed, but occurs at about 2 times higher illumination levels compared to the DC-mode. The photon counting curve output is linear within 90% and 50% up to about 15 MHz/cm^2 and 110 MHz/cm^2, respectively. The extended linear range for counting mode can be explained by the principal of count measurements when all pulses with amplitude above some threshold are counted. So, despite the dropping amplitude of the single pulses most of them still stay above the threshold and are counted by the detector. For higher intensities when the amplitude of the detected peaks is falling below the threshold, the count rate starts to saturate and then drops despite the increase of light intensity.

In some cases the reflection LIDAR profile can exceed the 100 MHz of average photon flux, requiring further improvement of the linear range of our detectors. Fig. 5 shows the output linearity vs anode current for conventional (blue curve) and High-Linearity (red curve) MCP-PMTs. For these measurements, the whole area (18 mm diameter) of the photocathode is homogeneously illuminated by a LED source and the MCP-voltage is set to provide a nominal photoelectron gain of 10^5. The conventional MCP-PMT has a MCP strip current of 8.5 µA (with parameters closed to the MCP-PMT presented above) and for the High-Linearity detector, the MCP strip current is 19 µA.

For the conventional MCP-PMT the output linearity drops to 90% at anode current of 0.32 µA (that is about 4% of the strip current) corresponding to 20 MHz rate of photoelectrons pulses. The High-Linearity MCP-PMT stays within 90% of the linear range up to 2.9 µA anode current, which is about 15% of the strip current. It means that the linear output range is increased by a factor of 9 compared to the conventional MCP-PMT. Thus, the maximum count rate (for 90% linearity) can be estimated to be 180 MHz or even 350 MHz (taking into consideration a factor of 2 extended linearity comparing to dc-mode, see Fig.4).

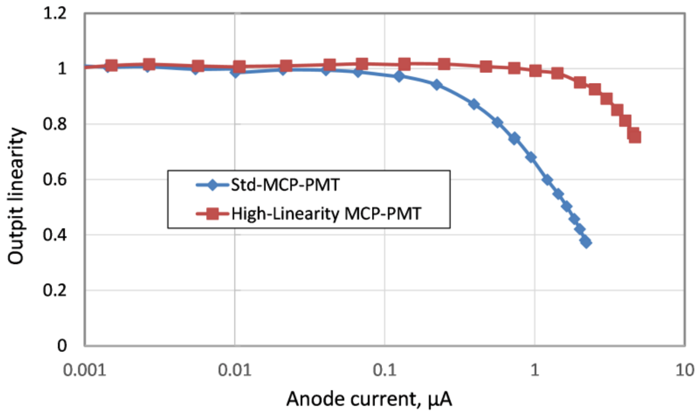

Figure 5. Output linearity vs anode current for conventional MCP-PMT (strip current of 8.5 µA) and for High-Linearity MCP-PMT (strip current of 19 µA). For these measurements full photocathode area of about 18 mm diameter is homogeneously illuminated by LED-source.

For a conventional MCP-PMT detector (the data is obtained with the same detector as for Fig.4) we have studied high-rate illumination regimes using counting technique with 100 ps pulse width 80 MHz laser [7] illuminating an 8 mm spot on the photocathode. The intensity of the laser is reduced, with average number of photoelectrons within a single pulse to be 3.2. Due to the high repetition rate, the detector operates in saturation regime.

Figure 6 shows the count rate of the detector within 100 ns time window measured by multiple-event time digitizer with a 100 ps time bin resolution. The counts are normalized per amount of recorded sweeps. The peak structure with a period of about 12.5 ns corresponding to 80 MHz laser excitation is clearly observed. The width of the individual peaks is about 320 ps and is mostly defined by the width of the laser pulse and the resolution of the multiple-event time digitizer with a 100 ps time bin. The total amount of events below each individual peak is found to be about 0.8 (see Fig.6).

Taking into consideration 0.04 probability of no photoelectron generation (based on Poisson distribution of photon generation) one can conclude that at 80 MHz laser excitation with 3.2 average number of photoelectron generation, it is about 84% of the peaks that can be detected despite a strong MCP saturation. The reason of this high rate detection capability is the increased amplitude of the detected peaks (in average 3.2 times higher than for single electron excitation in non-saturation conditions) that mostly stay above the threshold, allowing to detect almost all laser pulses even in saturation mode.

It has to be mentioned that this measurement does not provide the information about the number of photons arriving within a window below the time resolution of the detector (0.5-1 ns, see section 3.1). To derive information about the number of photons within a single peak additional measurements of the peak amplitude are required.

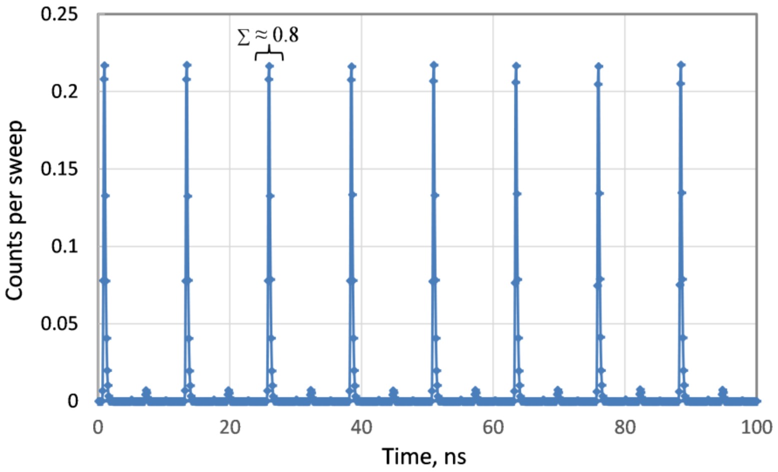

Figure 6. Counts (normalized with the number of sweeps) detected with illumination of central part of MCP PMT (8 mm diameter) by 80 MHz pulse laser. The intensity of the laser is adjusted corresponding to an average number of photoelectrons per single pulse to be 3.2. The data is shown for 100 ns time window. The measurements are done with the same MCP-PMT as for Fig.4.

4. CONCLUSIONS

The performances of Photonis MCP-PMTs are studied in the context of potential LIDAR application requirements. Photocathode characteristics combine an optimal spectral response and low dark rate for 355 nm and 532 nm lasers. The current operational lifetime is found to be about 9 C of integrated anode charge, with further improvement in progress. The implementation of high collection efficiency MCPs allows to increase the detective QE for about 50%. The excellent timing performance of single photoelectron detection allows to count precisely low flux of single photons. In a short time window, the maximum rate of detected pulses can reach about 1 GHz and can be increased in multi anode MCP-PMT configurations. It is also shown that for continuous high rate illumination, deviation from linear output takes place; for standard MCP-PMT the linearity within 90% will be kept to about 20-40 MHz of detected counts and for High-Linearity MCP-PMTs the linear range can be extended to about 200-350 MHz.

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