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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Test of the new hybrid INTEVAC intensified photocell for the use in air Cherenkov telescopes

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Abstract

For a new large diameter (17 m ∅ mirror collector) air Cherenkov telescope project a "camera" of photosensors with high, red extended quantum efficiency is needed. A candidate is a variant of the INTEVAC intensified photocell with a GaAsP photocathode (≈45% QE). A version with an avalanche diode as secondary amplifying element with fast (ns) single electron response is under consideration. The motivation for the development and first test results are discussed.

Keywords: High energy astroparticle physics detector; Hybrid photomultiplier

1. Introduction

The development of a new high QE, red extended, fast light sensor described in this paper is related to a new astroparticle physics detector for the study of GeV γ-ray sources. The new sensors are a key element for lowering the threshold and for increasing the sensitivity.

The currently most successful detection principle in the search for very high energy cosmic γ-ray sources is the observation of Cherenkov light generated by electromagnetic showers in the atmosphere. This principle allows one to observe low energy showers that stop high up in the atmosphere and which cannot be detected by ground based scintillation counter arrays. Standard air Cherenkov detectors are based on telescopes with a large mirror area that concentrate the Cherenkov light on a matrix of photomultipliers, the so-called camera. Analysis of the shower "image" allows for an efficient discrimination of the electromagnetic showers against the several orders of magnitude more frequent hadronic showers induced by the charged cosmic ray background.

Currently there exists an unexplored energy range between, say 10 GeV, the upper energy limit of γ-ray satellites, and ≈300 GeV, the threshold of the largest Cherenkov telescopes. The exploration of this energy gap, where important changes in astrophysical processes and also in the transparency of our universe occur, requires new high sensitivity telescopes. Prime observation targets for γ astronomy studies are active galactic nuclei (AGNs), weak galactic γ sources, such as supernova remnants (SNRs), X-ray binaries etc. and also the search for high energy gamma emission in gamma ray bursts (GRBs).

Modern telescopes based on photomultipliers (PMs) with bialkali photocathodes as light sensors reach an overall photon to photoelectron (PE) conversion ratio of about 8–12% and further gains in sensitivity can only be achieved by increasing the mirror size. The largest single dish, the Whipple 10 m ∅ telescope, has a threshold of 300 GeV. Presently, technical, optical and financial considerations prohibit the increase of mirror diameters beyond about 20 m. A possible means of lowering the threshold is to use high quantum efficiency (QE) photosensors with extended red sensitivity. Using extended red sensitivity seems contrary to the fact that the Cherenkov emission intensity increases with $1/\lambda^2$ and that the night sky background light increases with increasing wavelength. Atmospheric ozone cuts out all of the light below 290 nm and light losses due to Rayleigh and Mie scattering rise with $1/\lambda^4$, thus already at vertical incidence a significant fraction of the short wave Cherenkov light is lost. Red extended photosensors allow for high sensitivity air shower observations at large zenith angles where the UV component of the Cherenkov light is completely lost and the blue component is greatly reduced by Rayleigh and Mie scattering. Fig. 1 shows a Monte Carlo simulation of the emitted Cherenkov spectrum from vertically incident 50 GeV air showers and the spectral distribution after all losses (Rayleigh, Mie, ozone absorption, and various losses in the telescope).

Also indicated is the approximate spectrum after passing through air mass 4, e.g. from showers at declination angles around 75°. Only a small fraction of the remaining spectrum falls into the sensitive range of the bialkali photocathodes. With red extended photosensors even ob-

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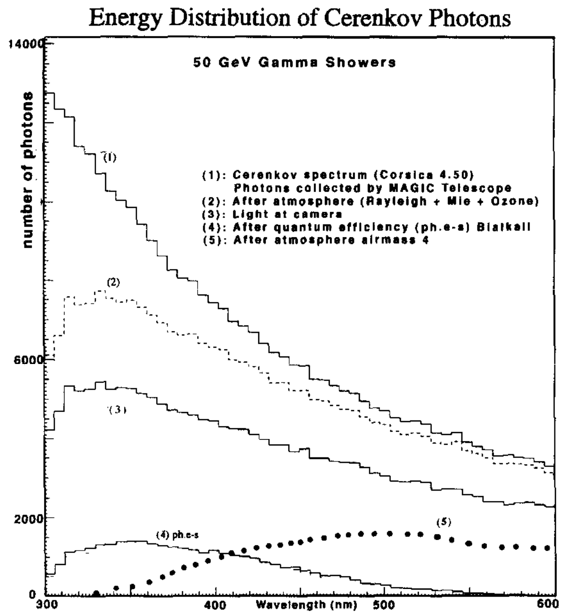

Fig. 1. Monte Carlo simulation of the Cherenkov light from vertical incidence 50 GeV air showers, initial spectrum and spectrum after various losses. The dotted curve indicates the spectrum from large zenith angles after passage of airmass 4. (From J. Carlos, University Madrid).

servations under moonlight become possible, albeit with somewhat higher threshold. Besides high QE the general requirements for sensors for Cherenkov telescopes are single electron response, resolving times of the order of a few ns and operation at high background light levels. The most efficient photosensors of 70–80% QE, silicon photodiodes or silicon avalanche photodiodes, are still unsuitable because of their high noise level preventing single photoelectron detection. Also large diameter diodes are limited in speed due to high capacitance. Recent developments for night vision units gave rise to GaAsP photocathodes of the so-called GenIII version. The QE approaches 50% in the visible range. Fig. 2 compares the QE of some modern photocathodes. For a 17 m ∅ air Cherenkov telescope project, Refs. [2,3], a new photosensor with a GaAsP photocathode is under consideration. It is planned to use a modified version of the commercial INTEVAC GaAsP photosensor.

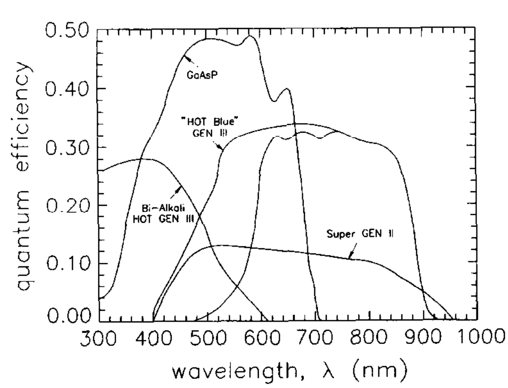

Fig. 2. Comparison of the QE of various photocathodes (original reference unknown).

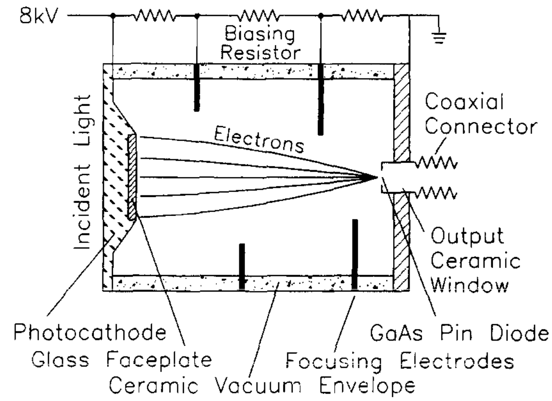

Fig. 3. Cross section of the commercial INTEVAC IPD.

2. The INTEVAC GaAsP intensified photocell as a parent type for a Cherenkov photosensor

The company INTEVAC offers a commercial photosensor with an 8 mm ∅ GaAsP photocathode. This rather compact detector is a hybrid PM (called an IPD by INTEVAC) with a 1 mm ∅ GaAs PIN diode as anode. Photoelectrons are accelerated by a cathode to anode voltage of 2–10 kV_{c-a} and generate up to about 1500 electron–hole pairs in the diode. Fig. 3 shows a cross-section of the tube and Fig. 4 the spectral curve (plain tube) of a sample tube when cross-calibrated against a

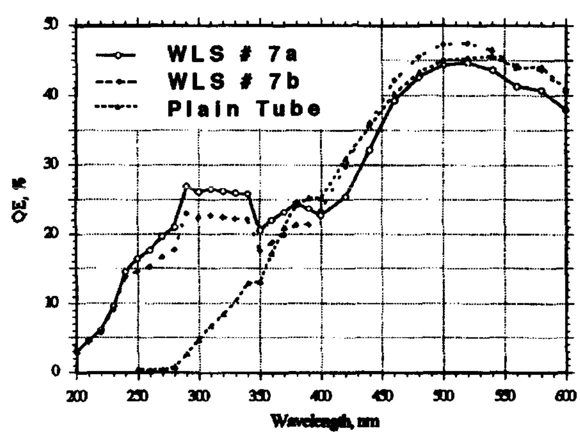

Fig. 4. Measured spectral sensitivity of an INTEVAC IPD without and with WLS coatings.

reference silicon photodiode. Some modifications are necessary in order to adapt the device to the envisioned use:

a) The QE below 400 nm is too low, i.e. below that of bialkali photocathodes. A solution to enhance the UV sensitivity with wavelength shifters (WLS) will be discussed in the next section.

b) The gain of the IPD is too low to achieve single electron response in the ns time domain. The output signal has to be amplified by a transimpedance amplifier or a very fast charge sensitive amplifier to a few mV per PE. Even the best fast amplifiers have an equivalent input noise charge of a few thousand electrons in the 1–10 ns time domain. Also we intend to operate the tube with lower acceleration voltage U_{c-a} because of possible high humidity in open air operation. The solution is to replace the diode by an avalanche diode giving additional gain. This development is discussed in Section 4.

3. Enhancing the UV sensitivity by WLS coating of the window

In order to make full use of the Cherenkov spectrum reaching the telescope, the UV sensitivity of the IPD has to be enhanced. A straightforward and simple procedure is to coat the window with a WLS that shifts the UV light to the wavelength of the IPD's maximum sensitivity. The WLS method has been in use for many years in high energy physics Cherenkov detectors where it offers a simple remedy for the UV cut-off of the PM glass windows. Fluorescent dyes, particularly those for dye lasers, are well suited to this use because many of them have a QE close to 100% and decay times in the ns range. These dyes can either be evaporated directly onto the window or embedded in a plastic carrier. The latter method is more efficient because of better light trapping, ease of application (as a foil or lacquer) and much higher mechanical resistance. Examples of lacquer coating of PM windows can be found in Refs. [4,5]. Some suitable dyes for our application are p-terphenyl, butyl-PBD, POPOP, modified perylene (BASF dye #078 or 241), etc. The dyes can be dissolved together with a polystyrene or paraloid (an acrylic laquer base) binder in organic solvents such as dioxan, chloroform or dichloromethane and applied as lacquer or thin foil to the window. The window can be overcoated a second time by a thin layer (a few microns) of teflon AF acting as a simple antireflex coating because of its low refractive index of $n = 1.3$. Tests of WLS coating on the IPD showed a clear increase of the UV sensitivity; see examples in Fig. 4. The gain did not reach the predicted value of around 40% because the current window geometry is not ideal for WLS light collection. For strength reasons a tapered glass window of 5.6 mm thickness, see Fig. 2, was used in the commercial tube. The WLS emits light isotropically. Besides the inevitable loss of ≈15% in the forward direction normally all light is trapped in the high refractive index glass and has a high probability of hitting the photocathode. In the case of the IPD's tapered 5.6 mm window about 45% of the light misses the cathode. This deficiency can be corrected by using a fiberglass plate or a thin, high strength artificial sapphire window. Fiberglass plates have other losses and are therefore unsuitable.

We have tested 1 mm thick sapphire windows (20 mm ∅) at up to 30 atm without breaking them. Sapphire is used in ultra high vacuum applications at up to 10^{-10} Torr and is easily available because of widespread use in wristwatch windows. Its thermal expansion coefficient of $\approx 6 \times 10^{-5}$ is closely matched to Kovar, to the ceramic material of the tube body and to GaAs. Its high melting point prevents melt bonding of the GaAsP wafer cathode directly onto the window but so-called solder glasses of matched expansion coefficient and a softening temperature of ≈350°C can be found readily. Due to its higher refractive index plain sapphire will have higher reflective losses than glass but, with the surface coating of the plastic WLS carrier and Teflon AF, the losses can be reduced to <3%. The window is normally fixed to the tube body by an indium seal. Our tests confirmed that a load of >1500 kg can be applied without breaking a 22 mm ∅, 1 mm thick artificial sapphire window. In summary, we are confident that one can achieve a QE > 40% from 300 to nearly 650 nm with the modified IPD. Due to the WLS decay time a small degradation of the time resolution will occur, but it will still be below the 1–2 ns time spread of the Cherenkov light.

4. The increase of the IPD gain

The gain of ≈1500 of the parent type IPD is too low for a good single electron response in the ns time domain. Recently in a prototype IPD, INTEVAC has replaced the GaAs PIN diode by a GaAs Schottky avalanche diode (AD). At a bias of ≈30 V the AP has an internal gain of 10–15 resulting in an overall device gain of ≈25 000 at 10 kV_{c-a}. GaAs allows for a very high operating frequency (up to 4 GHz in the IPD). As we have less demanding speed conditions we intend to replace the GaAs AP by a silicon one for the following reasons: we are interested in running the tube in rather harsh field environments and want to lower the U_{c-a} to <5 kV, thus the primary gain would be reduced. This reduction has to be compensated for by a higher AP gain. In addition we plan to raise the overall gain to about 40–60 000 because it follows for cheaper and less complex transimpedance amplifiers. A high gain in a GaAs-AP cannot be achieved because of the nearly equal k-factors of hole and electron multiplication. Silicon APs are now well under control up to gains of, say, 200 (see the review talk by J.P. Pansard on silicon avalanche photodiodes at this conference). Also the energy required to create an electron–hole pair in silicon is lower

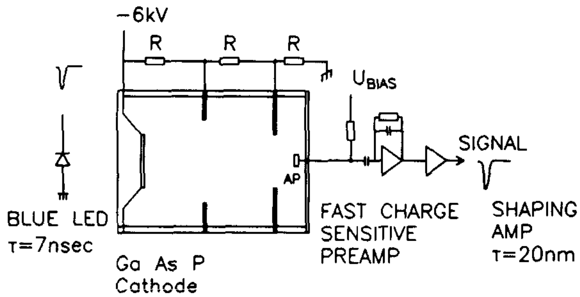

Fig. 5. Block diagram for a test of the modified INTEVAC IPD with avalanche diode readout.

than in GaAs (3.6 eV vs. 4.2 eV) thus the silicon AP will have a higher multiplication for the same U_{c-a}. In addition the lower Z of silicon compared to GaAs will result in less back scatter and hence give an intrinsically better single electron resolution.

We have tested the single electron response of the prototype IPD using a blue LED light pulser of 5 ns FWHM and $\langle n_{photon}\rangle \approx 6$–8. Fig. 5 shows the basic block diagram of the test set-up and Fig. 6 the resulting pulse height distributions for two sets of operational parameters. With 10 kV_{c-a} and a 50 ns filter time constant the peaks for $1, 2, 3\cdots$ electrons are well resolved while with 6 kV_{c-a} and a 10 ns filter time constant (i.e. settings much closer to our final operating conditions) the electron peaks are still distinguishable but much wider. The pulse height resolution deduced from Fig. 6a would be in principle just

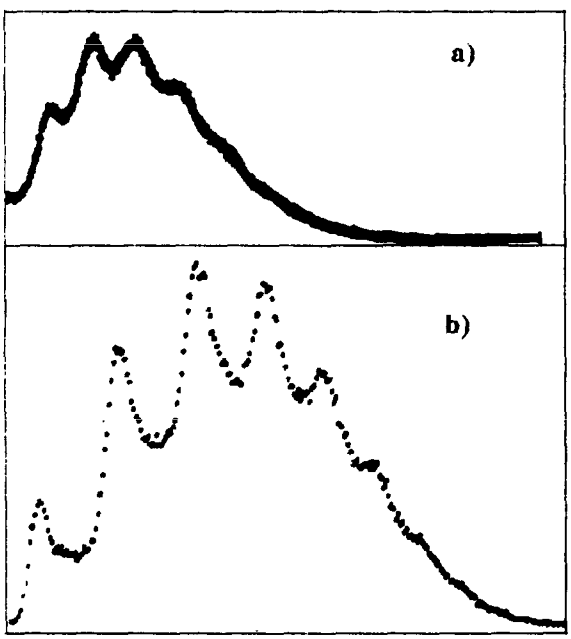

Fig. 6. Pulse height spectrum of a modified INTEVAC IPD when illuminated by a fast blue LED pulser. (a) $U_{c-a} = 6$ kV; $U_{AP} = 30.0$ V, $\tau = 10$ ns. (b) $U_{c-a} = 10$ kV; $\tau = 50$ ns.

acceptable for us but in a large system one would want to have better performance to counteract degradation due to component spreads and time. The use of a silicon AP of 1.5 mm ∅ and of gain 30–60 seems to be the best solution.

5. The ion feedback problem

In our application the photosensor will work in a high background environment. The large mirror will collect a high flux of the night sky background light ($\approx 10^{12}$ photons/m^2 serad s between 300 and 550 nm) resulting in a single photoelectron counting rate in excess of 50 MHz. While the probability of ionising the restgas between cathode and anode is low because of a vacuum of 10^{-8} Torr, the rate of ionisation of the restgas adsorbed on the AP surface and surrounding metal layer will generate a sizeable flow of ions. This back-flow (presumably mostly hydrogen ions) will have two adverse effects on the photocathode: (a) it will frequently generate large pulses that can fake large Cherenkov signals (see contributed paper from R. Mirzoyan et al. to this conference) and (b) it will destroy the activation of the photocathode. The ions can be deflected electrostatically such that they miss the photocathode. Fig. 7 shows a simulation of electron and ion tracks carried out by INTEVAC using their patented deflector, a small conductive finger at ground potential. The small deflection of the higher energy electrons is compensated for by a small offset of the AP from the center. A test of the prototype IPD with an 8 mm GaAsP photocathode gave a noise rate of ≈10 kHz, but a very low rate of large signals being compatible with the rate of Cherenkov signals of cosmic muons passing through the thick glass window.

6. Conclusions and discussion

The current studies show that

a) An acceptable UV extension of the spectral sensitivity can be obtained for GaAsP photocathodes by applying a WLS coating to thin windows;

b) That 1 mm thick artificial sapphire is a good window candidate because of its high strength.

c) That the replacement of the anode diode by an AP allows for sufficient gain to have a good single electron response at very high rates.

d) The high vacuum and proposed electron optics with an ion deflector prevents destruction of the cathode activation by ion feedback.

All the tests carried out so far indicate that the use of such a photosensor will increase the conversion yield of Cherenkov light to PEs by about a factor of 3 over conventional bialkali PMs when observing close to the zenith and about a factor of 8–10 at low altitude (≈15°) observations. The combination of a 17 m ∅ mirror with

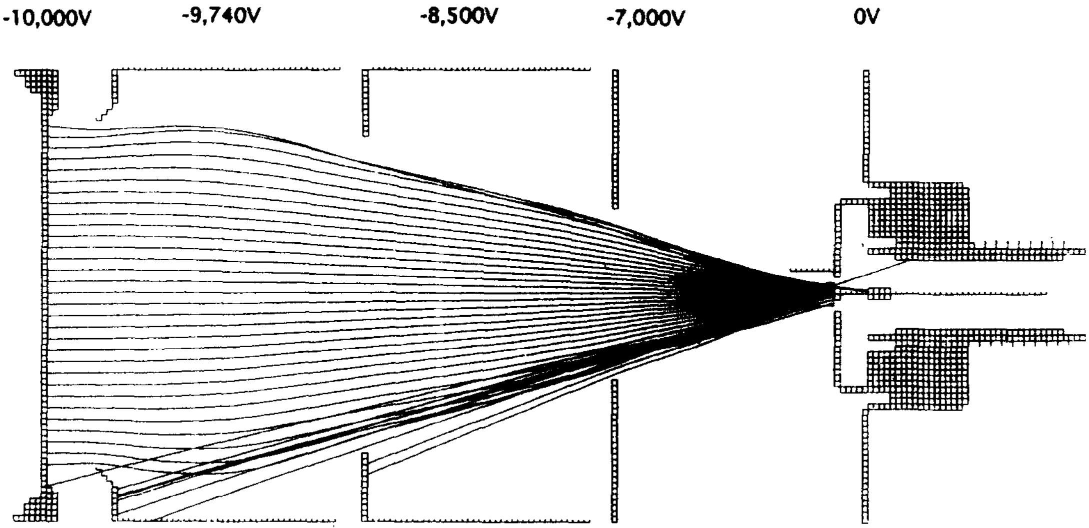

Fig. 7. Calculation of photoelectron and ion traces in the modified IPD. Calculation by INTEVAC.

such a sensor will have a detection threshold below 15 GeV for γ showers and thus overlap with the upper end of next generation γ satellites such as GLAST [6], but with about 10^4–10^5 times larger collection area and costs which are only a very small fraction of those for the satellite and the launch.

The ability to operate the telescope in the presence of moonlight will basically double the observation time compared to classical air Cherenkov telescopes.

The production of the tube is rather complex and therefore more expensive than the production of glass PMs with in situ formation of multialkali cathodes.

It should be noted that the device could have many other applications such as for example fast fluorescence studies of biological process or high resolution γ spectroscopy using CsI(TI) crystal detectors.

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