Photodetectors for HESS

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Abstract

HESS is a next-generation array of Imaging Atmospheric Cherenkov Telescopes (IACT) for the detection of cosmic gamma rays above 40 GeV, to be built in the Southern Hemisphere in the Khomas Highland of Namibia. In its final stage, the HESS experiment will consist of up to 16 telescopes each with a 80 m^2 reflector and 15 m focal length. The schedule foresees to start with scientific operation of the first 4-telescope subsystem in 2002 (Phase 1).

In the focal plane, each of the cameras contains ~700 photomultiplier pixels each viewing 0.16 deg. of the sky, giving a total field of view of 4.3 deg. A large part of the trigger electronics, analog signal storage, and control and monitoring electronics are integrated in the camera.

Key words: Imaging atmospheric Cherenkov telescopes; Photomultiplier tubes; Trigger threshold; Afterpulsing

1 Introduction

Detection of cosmic gamma rays in the energy window between ~10 GeV (the upper limit of satellite experiments) and a few tens of TeV allows a detailed study of the Nonthermal Universe, and probes many topics of fundamental astrophysical interest: the understanding of acceleration and emission mechanisms in galactic and extragalactic sources, the understanding of jet formation in active Galactic nuclei, the physics of pulsars and supernova remnants, as well as the study of extragalactic diffuse background photon fields.

Over the last decade, ground-based imaging atmospheric Cherenkov telescopes (IACTs) have emerged as the prime instrument for the detection of cosmic gamma rays in the TeV energy regime. The aim of next-generation IACTs is improved sensitivity, a lower energy threshold, good angular and energy resolution, and a large field of view. The stereoscopic observation of air showers with multiple telescopes, as pioneered in the HEGRA system of Cherenkov telescopes [1] [2], has been shown to be a powerful technique for TeV gamma ray observations.

The HESS project is a joint effort of collaborators from Germany, France, Italy, Ireland, the Czech Republic, Armenia, Namibia, and South Africa. The HESS experiment will consist of up to 16 telescopes in the Khomas Highland in Namibia in the Southern Hemisphere. For details of the HESS experiment, see [3] and [4]. HESS will have a detection threshold of about 40 GeV and an angular resolution a few arcminutes. The flux sensitivity above 100 GeV of 10^{-12} ph/(cm^{2}s) is more than one order of magnitude better than currently achieved in IACT experiments. This should allow the observation of a significant number of objects and new source populations at GeV-TeV energies.

2 The IACT Technique

IACTs use a matrix of photomultipliers (PMTs) in the focal plane of a segmented mirror in the Davies-Cotton geometry to detect the light flashes from Cherenkov light generated by ultra-relativistic charged secondary air shower particles against a large background due to the light of the night sky. Characteristics of the Cherenkov light are a small (a few ns) time dispersion, a spectrum convoluted with atmospheric absorption which "peaks" at 300 - 400 nm, and a low (10 - 100 ph/m^2) photon density. To trigger the camera, typically a coincidence between a number of PMTs is required, with the signal in each PMT exceeding some threshold q_0. The air shower is imaged to a roughly elliptical shape in the camera, and the direction, energy and species of primary particle can be determined from the image. Stereoscopic observations of air showers, i.e., the simultaneous detection of air showers with two or more Cherenkov telescopes under widely varying viewing angles, allow an unambiguous determination of the shower axis. This together with the high background suppression by a multi-telescope coincidence trigger give a good angular and energy resolution, a low energy threshold, and reduction and control of systematic errors.

3 The HESS camera and trigger

The HESS camera development is based on the experience gained from the CAT [5] and the HEGRA experiments [6]. For the Phase 1 telescopes, only conventional PMTs are considered. For the second generation of telescopes, cameras with higher quantum efficiency photodetectors may be an option. The

HESS cameras consist of ~700 pixels (whereby a pixel is defined as the PMT and the accompanying electronics) arranged in a roughly circular fashion. The PMT spacing is 42 mm, corresponding to a viewing angle of 0.16 degree. The total field of view is 4.3 deg. Additional rings of PMTs can be added to increase the field of view to 5 deg. The maximal active camera diameter is 1.4 m. Each PMT is connected to a HV card containing a DC-DC converter and an actively stabilized base. A large part of the trigger electronics, analog signal storage, and control and monitoring electronics will be contained in the camera. This provides short paths for the fast analog signals in order to allow short gate times, thereby minimizing the night sky background noise and uncertainties due to timing jitter. The trigger electronics consist of a first level single pixel trigger and a second level topological trigger in the camera. The single pixel threshold will be ~4 photoelectrons. The third level global trigger fires if a minimal number of telescopes have triggered within a short coincidence window.

4 Requirements on Photomultipliers for HESS

Characteristics of the Cherenkov light and the night sky background (NSB) govern the requirements on the photodetectors. The energy threshold is dictated by the noise trigger rate due to the NSB. Due to the NSB illumination, large amplitudes due to afterpulsing of the PMTs determine the minimal threshold value for a given maximal acceptable noise trigger rate [7] [8]. The NSB has been measured to $\sim 2 \cdot 10^{12}$ ph/(m^2 st s) at the site of the HEGRA experiment [9], which for HESS implies an estimated photoelectron rate per pixel due to the NSB of 100 MHz.

For HESS, the requirements for the photomultipliers (PMTs) are the following:

- PMTs should be fast with a short (<2 ns) rise time and a small timing jitter, to maximize the signal-to-noise ratio, and to minimize the coincidence overlap with neighboring pixels for the trigger
- single photoelectron resolution, due to the small number of Cherenkov photons in the image and for calibration purposes
- low afterpulsing rates, in order to reduce the trigger threshold and thus the energy threshold
- linearity over a range of 1 - 2000 photoelectrons, to reconstruct showers in the energy range of 40 GeV to >20 TeV
- high quantum efficiency in the 300 - 600 nm range, with a limited spread ~ ±15% between PMTs
- a dark current much smaller than the anode current due to the NSB
- operation at low ($\sim 2 \cdot 10^5$) gain, to minimize the effects of aging due to the high NSB flux ($\sim 3.2\mu$A anode current, total charge over the experiment

lifetime ~100 C)
- good cathode uniformity: the cathode non-uniformities give an additional amplitude uncertainty for the small number of photoelectrons in a typical Cherenkov image

5 Photomultiplier Tests

In order to select PMTs for the Phase I of HESS and to optimize the external circuitry, a number of test benches were built up to measure pulse shape, dark current, single photoelectron response, gain, cathode uniformity, linearity, quantum efficiency, and afterpulsing behaviour. PMTs with a 28 to 38 mm diameter from Electron Tubes Inc. (9102KA, 9125A, 9134A), Hamamatsu (R580, R7525), and Photonis (XP2972, XP2962, XP2960) were investigated. All PMTs had bialkali photocathodes and a linear focused dynode structure. Most measurements used a linear voltage divider with a ratio of 2:1:1:...:1 with the cathode on negative high voltage. For DC illumination, a Xenon lamp together with a variable monochromator was used. Short light pulses were produced with a nitrogen laser working at 337 nm. A scintillator shifts the wavelength of the laser light to ~370 nm.

Single photoelectron spectrum
The single photoelectron (SPE) spectrum was determined by feeding the anode signal to a charge-sensitive preamplifier, a shaping amplifier, and a 13-bit spectroscopy ADC. The peak-to-valley ratio, the pulse height resolution, and the PMT gain are determined from the SPE curves (see Fig. 1). The gain of the electronics chain is calibrated by injecting charges of known value into the preamplifier.

Cathode uniformity
The cathode uniformity is measured using an illuminated 1 mm pinhole in front of the cathode. An X-Y translation stage moves the PMT over the pinhole in a grid of steps with 1 mm spacing, and the anode current is read out at each point using a I/U converter and a 13-bit ADC. A silicon diode is used to monitor the light flux, and the anode current is corrected to the diode flux. A typical scan result is shown in Fig. 2. For HESS, light concentrators in front of the PMTs focus the incoming flux to the inner 21 mm of the photocathode. The rms deviation from uniformity within a 21 mm aperture ranged from 8% - 16%.

Linearity
The linearity is measured by illuminating the photocathode with short (~ ns) pulses from a nitrogen laser. Using a variable attenuator, the PMT amplitude is determined as a function of light intensity. A silicon diode is used to measure

the flux of each laser pulse, and the PMT amplitude is corrected to the diode flux. The measurements show a degradation of the linearity if the output is at a dynode instead of the anode. The use of a progressive voltage divider improves the linearity.

Quantum efficiency
The quantum efficiency is determined by measuring the cathode current for a given illumination. A Xenon lamp with a programmable monochromator from 1 - 1000 nm is used to step through wavelengths. The illumination is determined with a calibrated silicon diode, and light and dark measurements are performed at each wavelength to subtract the cathode dark current. The measured quantum efficiency of two PMTs is shown in Fig. 3. A detailed study of the systematic uncertainties gives errors of $\pm 7\%$.

Afterpulse rate
The afterpulse rate is measured by illuminating the PMT with a flux comparable to the NSB expected for HESS, and measuring the integral count rate over a given threshold by feeding the amplified anode signal onto a discriminator and a counter. The discriminator threshold is calibrated in units of photoelectrons by differentiating the rate vs. threshold curve for weak illumination, yielding a single photoelectron spectrum (Fig. 4, right).

Fig. 4 (left) shows the integral count rate as a as a function of photoelectrons for five PMTs of the same type for an illumination of 100 MHz photoelectron rate and a gain of $2 \cdot 10^5$. Below $\sim$2 photoelectrons, the counter used for the measurement saturates due to the high count rate. Below $\sim$5 photoelectrons, the count rate is dominated by pileup pulses. The “tail” at higher numbers of photoelectrons is due to afterpulses. The “tail” is fitted by a function $R_{ap} = R_{pe} \cdot a \cdot exp(-q_0 \cdot b)$ with R_{pe} as the photoelectron rate, and q_0 as the threshold in photoelectrons. Typical values are 0.2-0.5 for b, and 0.01-0.0001 for a. One can see from Fig. 4 that the afterpulsing rates can vary by an order of magnitude even for the same type of PMT. This is due to variations in the quality of the vacuum as well as the differences in HV needed to reach the same gain.

6 Conclusions

HESS is an IACT-System of the next generation for gamma-ray astronomy in the 100 GeV energy range. HESS will have a high sensitivity, good energy reconstruction for spectroscopy, and a large field-of-view for the observation of extended sources.

The camera of the Phase I telescopes will use fast PMTs with bialkali photocathodes operated at low ($\sim 2 \cdot 10^5$) gain. The schedule foresees the installation of the first camera by end of 2000, and first scientific observations with the four-telescope subsystem in 2002.

In order to find the optimal PMT for HESS and to optimize the voltage divider, we have developed a number of well-understood, calibrated setups to characterize PMTs. The measurements show that PMTs of several manufacturers can fulfill the requirements needed for HESS. Measurements of the spatial uniformity of the anode sensitivity show that ~30 mm diameter PMTs are sufficiently large. There are systematic differences in the afterpulse rates of different manufacturers. A final decision on the PMT for HESS will also be based on financial factors.

References

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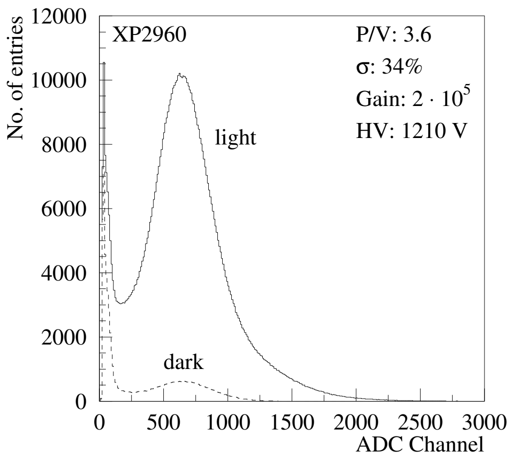

Fig. 1. *A single photoelectron spectrum ("light") and the dark-current pulse spectrum ("dark"). The peak-to-valley ratio (P/V), the relative width (σ) of the peak, the gain, and the high voltage (HV) are shown.*

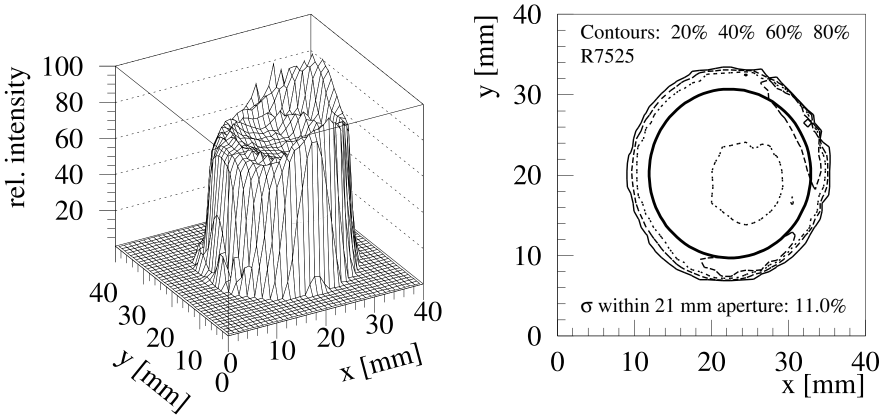

Fig. 2. *The relative anode sensitivity is shown as a function of the cathode position as a surface (left) and a contour (right) plot. Only the inner 21 mm region of the photocathode will be illuminated for the HESS PMTs (circle in the right-hand plot). The rms deviation from uniformity within a 21 mm aperture is 11%.*

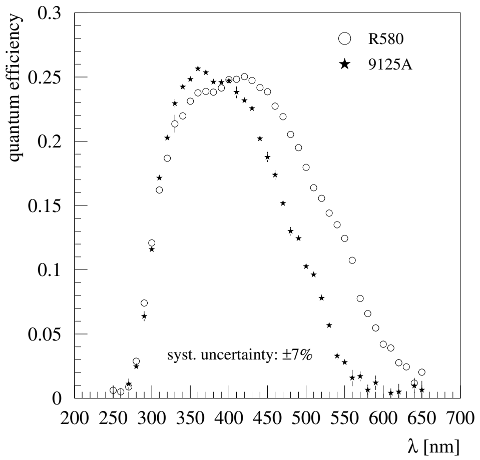

Fig. 3. *The measured quantum efficiency as a function of wavelength is depicted for two PMTs.*

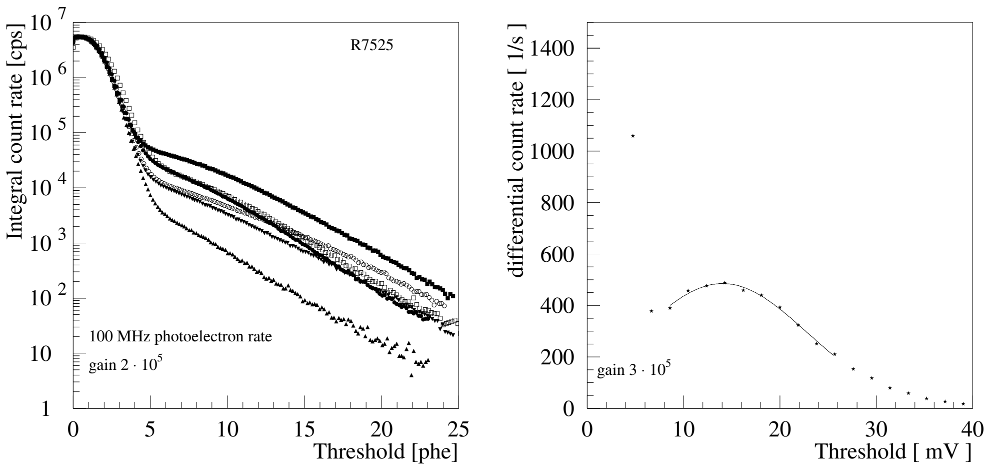

Fig. 4. *The left-hand plot shows the integral count rate as a function of the threshold in photoelectrons for five PMTs of the same type. The "tail" above ∼5 photoelectrons is due to afterpulsing. The right-hand plot shows the calibration of the threshold at low illumination: the differential count rate is determined as a function of the discriminator threshold, giving a single photoelectron spectrum.*