



Status of the First G-APD Cherenkov Telescope (FACT)

T. BRETZ³, H. ANDERHUB¹, M. BACKES², A. BILAND¹, A. BOLLER¹, I. BRAUN¹, V. COMMICHAU¹, L. DJAMBAZOV¹, D. DORNER⁴, C. FARNIER⁴, A. GENDOTTI¹, O. GRIMM¹, H.P. VON GUNTEN¹, D. HILDEBRAND¹, U. HORISBERGER¹, B. HUBER^{1a}, K.-S. KIM^{1b}, J.-H. KÖHNE², T. KRÄHENBÜHL¹, B. KRUMM², M. LEE^{1b}, J.-P. LENAIN⁴, E. LORENZ^{1c}, W. LUSTERMANN¹, E. LYARD⁴, K. MANNHEIM⁵, M. MEHARGA⁴, D. NEISE², F. NESSI-TEDALDI¹, A.-K. OVERKEMPING², F. PAUSS¹, D. RENKER^{1d}, W. RHODE², M. RIBORDY³, R. ROHLFS⁴, U. RÖSER¹, J.-P. STUCKI¹, J. SCHNEIDER¹, J. THAELE², O. TIBOLLA⁵, G. VIERTEL¹, P. VOGLER¹, R. WALTER⁴, K. WARDA², Q. WEITZEL¹

¹ETH Zurich, Institute for Particle Physics, Schafmattstrasse 20, CH-8093 Zurich, Switzerland

²Technische Universität Dortmund, Experimental Physics 5, Otto-Hahn-Str. 4, D-44221 Dortmund, Germany

³École Polytechnique Fédérale de Lausanne, Laboratory for High Energy Physics, CH-1015 Lausanne, Switzerland

⁴ISDC Data Center for Astrophysics, Center for Astroparticle Physics, Observatory of Geneva, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland

⁵Universität Würzburg, Institute for Theoretical Physics and Astrophysics, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany

^aalso at University of Zurich, CH-8057 Zurich, Switzerland

^balso at Kyungpook National University, Center for High Energy Physics, 702-701 Daegu, Korea

^calso at Max-Planck-Institut für Physik, D-80805 Munich, Germany

^dalso at Technische Universität München, D-85748 Garching, Germany

thomas.bretz@epfl.ch

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Abstract: In the past years, the second generation of imaging air-Cherenkov telescopes has proven its power detecting weak sources with high sensitivity and low energy threshold. The goal to further improve the sensitivity and lower the energy threshold requires a robust and highly efficient sensor technology. A promising detector technology are silicon based photon detectors, namely Geiger-mode avalanche photo-diodes (G-APDs). They promise robustness and easy manageability compared photo-multiplier tubes so far in use.

To prove the applicability of this technology for Cherenkov telescopes, one of the former HEGRA telescopes was revived and will be equipped with a camera using G-APDs as photo sensors. Since G-APDs are comparably small, solid light guides are used to significantly increase the light collection area of each sensor. With this technologies, the First G-APD Cherenkov Telescopes (FACT) promises an increase in sensitivity and decrease in energy threshold, compared with a classical photo-multiplier based camera.

Keywords: IACT G-APD Geiger-mode Cherenkov telescope FACT

1 Introduction

The current generation of Cherenkov telescope, H.E.S.S., MAGIC and VERITAS, has been a great success. In this context, a new and more powerful instrument, the Cherenkov Telescope Array (CTA) is under development. It is supposed to explore the whole sky with an even higher sensitivity to gain a reasonable statistical basis for analysis, but also to further lower the energy threshold to get into an overlap region with satellites. A further goal is to increase the dynamic range of the observed energy, so that sources can be detected with high flux at low energies, but also their high energy emission or their cut-off at high energies can be detected with reasonable statistics at the same time.

Current instruments, but also CTA, are and will be busy with their discovery programs. But high statistics of sources is not the only source of important information for the understanding of the observed flux variations, but also continuous and long-term monitoring. Due to their discovery potential, the observation time of the most sensitive instruments is too valuable to be spent for long-term observation programs on known sources. Therefore, and for the high energy detection in CTA, small and inexpensive Cherenkov telescopes are of high interest. For the costs, not only development and production cost, but also maintenance and operation costs are important. Using Geiger-mode avalanche photo diodes (G-APDs) instead of Photo-

multiplier tubes (PMTs) for photo detection seems to be a very promising, inexpensive and robust technology.

The camera of the First G-APD Cherenkov Telescope (FACT) is build to prove that G-APDs are an inexpensive and easy to handle alternative to PMTs, and to gain experience in operating such a device. In the most likely case that FACT can be operated successfully, it will serve as a monitoring telescope, dedicated to the observation of the brightest known blazars.



Figure 1: The FACT telescope at La Palma with the newly refurbished mirrors awaiting the camera to be installed.

2 Overview

The telescope is located on the Observatorio Roque de los Muchachos at the Canary island La Palma. For the installation of the camera, the former HEGRA CT3 telescope mount was used which is still in place. In the past years the drive system has been exchanged with a system very similar to the drive system used for the close-by 17 m MAGIC telescopes, but scaled down in power. Additionally, the old CT3 mirrors have been replaced by the refurbished CT1 mirrors. In contradiction to the CT3 mirror, these mirrors are hexagonal which increases the effective mirror area to 9.5 m^2 . The refurbished mirrors also have an improved reflectivity due to their new coating.

The camera consists of 1440 channels. Each channel is equipped with a Geiger-mode avalanche photo diode (G-APD) and a solid light-concentrator. After pre-amplification, nine channels are summed at a time to build the trigger signal. The summed analog signal is discriminated. The digital trigger signal is build by an OR of all trigger patches. To ensure a good timing, the time jitter of the trigger signal, distributed to the readout boards, is well below 1 ns.

For the readout, the DRS4 analog ring-buffer is used which stores the analog signal until the trigger signal arrives. Finally, the signal is digitized by a 25 MHz ADC. Storage of the signal in the DRS can be adjusted between 800 MHz and 5 GHz. The anticipated sampling frequency is 2 GHz.

The electronics is build on eighty boards, forty pre-amplifier with trigger mezzanine boards and forty read-

out boards plugged into four crates. Each board contains the readout chain of 36 channels. Except the G-APD bias-power supply, all electronics is integrated into the camera. Communication and data transmission is done over forty Ethernet connection routed through two Ethernet switches and connected to four Ethernet cards in the data acquisition PC.

For details on the electronics see [1].

2.1 Usage of G-APDs

Geiger-mode avalanche photo diodes (G-APDs) have a couple of advantages compared to classical Photomultiplier tubes (PMTs). Since G-APDs are silicon based semi-conductors they are mechanically more robust and due to their small size, insensitive to the Earth's magnetic field. Furthermore, the voltages which need to be applied are in the order of 70 V and therefore much lower compared to typical PMT voltages which are in the order of kilo-volts.

As typical disadvantages of G-APDs usually their small size, high dark count rate, their high afterpulsing probability, their internal optical crosstalk and the temperature dependance of their properties are mentioned. Looking into these probabilities in more details, it turns out that for Cherenkov telescopes neither of them is of any real disadvantage.

2.1.1 Physical size

G-APDs used in FACT have a sensitive area of 9 mm^2 . Compared to PMTs with typical diameters in the order of one inch this seems to be quite small. In Cherenkov telescopes using PMTs, so called optical light guides are usually used to fill the dead space between the PMTs and redirect the light on the sensitive area. These light guides are usually not optimized for the best light compression rate, since this would increase the sensitive area too much and either the telescope system would become too huge or the pixel's field-of-view on the night-sky would become too large. For G-APDs, light guides can be optimized for best compression. Furthermore, the size of the light-guides is small enough that solid light guides can be used and do not suffer much from transmission losses. In fact, they reduce Fresnel losses if glues to the sealing window and the G-APD. Due to total reflection also the reflection losses are reduced. Taking all this into account, solid light concentrators can give compression ratios of larger than 10, up to 17 (in FACT: ≈ 10)

For details on solid light concentrators see [2].

2.1.2 Dark count rate

At typical operation temperature (room temperature), the dark count rate of a G-APD as used for FACT is in the order of 5 MHz. Compared to the typical count rates for photons from the diffuse night-sky background, which, in our case, are in the order of 50 MHz, this is negligible.

2.1.3 Optical crosstalk

With typical crosstalk probabilities in the order of 15% to 20% G-APDs have a quite high uncertainty on the single photon level. However, in Cherenkov astronomy single photon counting is not important. For larger signals the optical crosstalk just increases the average signal by the crosstalk probability. Since the additional fluctuations introduced by these effect are still smaller or at least in the same order than fluctuations in the shower development. Also this effect can be neglected.

Since the FACT camera has 1440 channels of which nine channels are summed together at a time to build the trigger signal, crosstalk signals in single channels in the order of the height of the trigger threshold become important. The rate of high crosstalk events which are by chance in coincidence with small signals in neighboring channels are already in the order of the expected trigger rate,

To solve this issue two options are considered:

- Upgrade of the sum-trigger system to limit the signal contribution from a single channel.
- Applying a software trigger. For a software trigger the camera has to be read out at a very high rate corresponding to a low threshold. A software-trigger checks the two-dimensionality of each event before the event is passed for storage and further analysis. Another advantage of this method is that the exact trigger condition is known for a proper analysis of the data.

2.1.4 Afterpulses

The afterpulse probability of G-APDs is usually higher than the afterpulse rate of PMTs. The main difference is their time profile. While the probability for afterpulses of PMTs usually has a peak in its time profile, the probability of afterpulses of G-APD drops exponentially after the initial avalanche with a time-constant comparable to the falling edge of the signal. Consequently, afterpulses of G-APDs are not correlated amongst several chips and therefore can't fake additional triggers as it can happen with afterpulses in PMTs. Furthermore, if a G-APD cell was hit the cell needs some time for recovery in which afterpulses either do not induce further avalanches, or the charge released by the avalanche is further attenuated. Due to this, afterpulses in G-APDs mainly effect the falling edge of the pulse. Since Cherenkov astronomy is mainly interested in the position of the pulse and its amplitude, the falling edge can simply be neglected. Since the introduced afterpulse cannot trigger the trigger system due to fake correlations, they are of no importance for Cherenkov telescopes.

2.1.5 Temperature dependence

Most properties like the photo detection efficiency, the afterpulse rate, the optical crosstalk and the dark count rate of G-APDs depend strongly on the chip's temperature.

This temperature dependence comes from the change of the breakdown resistor and effectively changes the voltage applied, the so called bias voltage. By changing the applied voltage, the bias voltage can be brought back to its nominal value and hence the chip's properties can be maintained. The only bias voltage independent property, is the dark count rate, so that a maximum temperature (in the order of 35deg) should not be exceeded.

Temperature limit Using a good heat isolator between the sensor compartment and the electronics compartment of the camera, normal convection and temperatures at night at La Palma not exceeding 30deg, are enough to keep the temperature in the sensor compartment below 35deg and keep the dark count rate at a reasonable number.

Feedback system To maintain the bias voltage a feedback system has been setup. Since the photo detection efficiency of the G-APD depends on the bias voltage, a stable photon signal can be used to adapt the applied voltage. Measuring the average amplitude of signals from a temperature stabilized light pulser, the applied voltage can be adapted accordingly and the bias voltage can be kept stable. A very important additional advantage is that the response of all channels to light pulses is kept stable which ensures a stable trigger response. In principle such kind of effects can also be corrected by offline calibration, but in this case the analysis has to take the changing trigger response into account which is very difficult.

3 Calibration

Another advantage compared to PMTs is that it is very easy to obtain a single photo electron spectrum. This allows to determine the absolute gain of each chip individually. Correlating this with the discussed feedback mechanism, does not only allow to keep the gain stable, but also absolutely calibrated.

Therefore, a single photo-electron spectrum for each pixel is measured. This is done first with closed camera lids and the dark counts. Now the feedback system is used to change the applied voltages to set the nominal gain of each G-APD. The external light pulser is switched on and the average amplitude in each channel is stored as reference. This is now redone for different pointing position on the sky, all chosen to have the least possible number of bright stars in the field-of-view. With an outlier detection and averaging the final reference is deduced.

During operation intermediate light-pulser events are analysed and their average amplitude is kept stable with the help of the feedback system.

Since the feedback value is determined from the average pulse height in each channel, while the bias voltage is applied to four or five pixels at once, the effect of a lower gain due to saturation of the G-APDs cells by noise photons from bright stars can be excluded. For regions with a mainly homogeneous night-sky background, like the typical regions around the extragalactic sources, which are the

main target object of FACT, even a single correction value for the whole camera can be calculated.

For more information on the feedback system and the calibration see [3].

4 Status

All electronics has been build and tested. After continous full system tests, ongoing for several weeks, the camera has recently (13/09/2011) been closed to ensure continous operation over a reasonable time-scale, before the camera is shipped to La Palma.

All components have passed their tests. Components which showed problems were replaced with spare parts. All components work within their specifications. Three pixels (out of 1440) show weird signals, which is most probably due to a not well done grounding, two pixels are dead. Repairing these pixels is quite complicated, since the sensor compartment is very densely packed. The collaboration has decided to switch off these pixels in the trigger sum for the first tests in La Palma.

A single photo-electron spectrum could be extracted from all working channels. Both light-pulsers, the internal and external one show reasonable and stable signals.

The camera control and readout is working properly and stable. Sometimes at startup Ethernet connection problem with single readout boards were encountered and could be traced back to a bug of the Ethernet chip in use. Due to the high number of boards sometimes a couple of software induced resets need to be emitted which results in starup times for the camera of several minutes. Fortunately, this problem neither effects data-taking nor stable operation. Total transfer rated through the four Ethernet card of the PC of up to 350MB/s could be reached which corresponds to reading the full DRS chain of 1024 samples of all 1440 channels with a rate >80 Hz. The rate does not scale linearly with the number of samples read from the chips because at very high rate filling of the Ethernet buffer (which has to take place more often) becomes dominant. Nevertheless, with a region-of-interest of 100 samples rates up to 400 Hz can be achieved. It is already clear that this can be further improved with an more advanced FPGA firmware on the readout boards.

For a direct hardware trigger, a data rate around 30 Hz is expected and the desired region-of-interest is 100 samples. Consequently, the readout is well within its specifications.

For a software trigger, a reasonable data rate would be in the order of 1 kHz, which is achievable with firmware upgrade.

For more details on existing measurements and test results see [4].

5 Conclusion

All lab tast performed in the last weeks were successfull. All parameters are within their specifications. Also on-

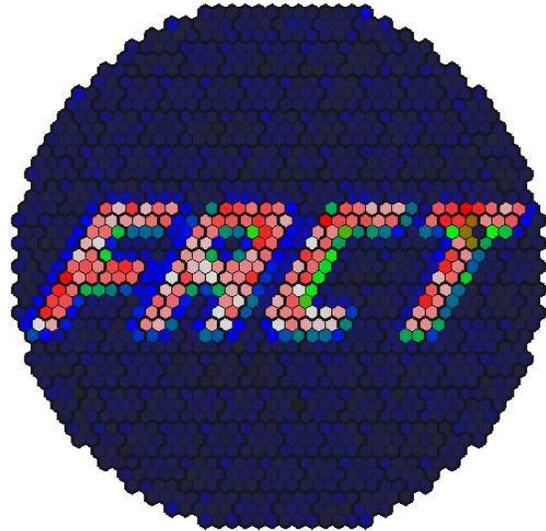


Figure 2: Maximum amplitude of an event from the external light-pulsers with a cover in front of the camera.

going stability test do not show major problems. Shipment is scheduled. The camera is supposed to arrive in La Palma end of September 2011. Comissioning and operation will start directly after installation beginning of October 2011.

As soon as all calibration measurements at the site are finished, standard operation will be carried out. Since the detection of new sources is not the goal of the project, the FACT collaboration can publicize their data immediately after data talking. This can be an important potential for the development of future software projects.

From the current experience of the FACT project it can already be concluded that G-APDs are an important alternative for future Cherenkov telescopes.

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