

# Technical Performance of the MAGIC Telescopes

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**Abstract.** The MAGIC-I telescope is the largest single-dish Imaging Atmospheric Cherenkov telescope in the world. A second telescope, MAGIC-II, will operate in coincidence with MAGIC-I in stereoscopic mode. MAGIC-II is a clone of MAGIC-I, but with a number of significant improvements, namely a highly pixelized camera with a wider trigger area, improved optical analog signal transmission and a 2-4 GSps fast readout. All the technical elements of MAGIC-II were installed by the end of 2008. The telescope is currently undergoing commissioning and integration with MAGIC-I. An update of the technical performance of MAGIC-I, a description of all the hardware elements of MAGIC-II and first results of the combined technical performance of the two telescopes will be reported.

**Keywords:** MAGIC, VHE, performance.

## I. INTRODUCTION

The 17m diameter MAGIC [1] telescope is as of today the largest single dish Imaging Atmospheric Cherenkov telescope (IACT) for very high energy gamma ray astronomy with the lowest energy threshold among existing IACTs. It is installed at the Roque de los Muchachos on the Canary Island La Palma at 2200 m altitude and has been in scientific operation since summer 2004. In the past years MAGIC has been upgraded by the construction of a twin telescope with advanced photon detectors and readout electronics. The two telescope system, is designed to achieve an improved sensitivity in stereoscopic/coincidence operation mode and simultaneously lower the energy threshold.

All aspects of the wide physics program addressed by the MAGIC collaboration ranging from astrophysics to fundamental physics will benefit from an increased sensitivity of the instrument. The expected lower energy threshold of the MAGIC two telescopes will have an impact on pulsar studies and extend the accessible redshift range, which is limited by the absorption of high energy  $\gamma$ -rays by the extragalactic background light. Simultaneous observations with the FERMI satellite will allow detailed studies of the high energy phenomena in the Universe in the wide energy range between 100 MeV and 10 TeV.

Detailed Monte Carlo studies have been performed to study the expected performance of the telescope system [3]. In stereo observation mode, i.e. simultaneously observing air showers with both telescopes, the shower reconstruction and background rejection power



Fig. 1: The two MAGIC telescopes in April 2009. The first telescope, on the left, operates regularly since 2004. The second telescope can be seen on the right. The frame, mirrors, active mirror control and drive hardware were installed in Summer 2008.

are significantly improved. This results in a better angular and energy resolution and a reduced analysis energy threshold. The overall sensitivity is expected to increase by a factor of 2 over the whole energy range and foreseeably larger below 100 GeV. Following the results of a dedicated MC study showing moderate dependence of the sensitivity on the distance of the two telescopes the second MAGIC telescope has been installed at a distance of 85 m from the first telescope.

In order to minimize the time and the resources required for design and production the second MAGIC telescope is in most fundamental parameters a clone of the first telescope. The lightweight carbon fiber reinforced plastic telescope frame, the drive system [2] and the active mirror control (AMC) are only marginally improved copies of the first telescope. Both telescopes will be able to reposition within 30-60 seconds to any sky position for fast reaction to GRB alerts.

Newly developed components are employed whenever they allow cost reduction, improved reliability or most importantly increased physics potential of the new telescope with reasonable efforts. Larger 1 m<sup>2</sup> mirror elements have been developed for MAGIC-II reducing cost and installation efforts. The newly developed MAGIC-II readout system features ultra fast sampling rates and low power consumption. In the first phase the camera has been equipped with increased quantum efficiency (QE) photomultiplier tubes (PMTs), while a modular camera design allows upgrades with high QE hybrid photo detectors (HPDs). A uniform camera with 1039 identical 0.1° field of view (FoV) pixels (see figure II)

allows an increased trigger area compared to MAGIC-I.

The entire signal chain from the PMTs to the FADCs is designed to have a total bandwidth as high as 500 MHz. The Cherenkov pulses from  $\gamma$ -ray showers are very short (1-3 ns). The parabolic shape of the reflector of the MAGIC telescope preserves the time structure of the light pulses. A fast signal chain therefore allows one to minimize the integration time and thus to reduce the influence of the background from the light of the night sky (LONS). In addition a precise measurement of the time structure of the  $\gamma$ -ray signal can help to reduce the background due to hadronic background events [9].

Both telescopes can be seen in figure 1. The frame of MAGIC-II and a fraction of the mirrors were installed back in 2007. The remaining hardware was installed in the Summer 2008. The telescope is currently undergoing extensive tests and integration with MAGIC-I. The system of two telescopes will end its commissioning phase in Fall 2009.

The telescopes have been recently renamed “MAGIC Florian Goebel Telescopes” in memory of the project manager of MAGIC-II, who died shortly before completing the telescope in 2008.

In the following the main technical features of the second telescope and several upgrades to the first telescope are discussed. References to more detailed contributions to the same conference are provided. A description of the performance of the two telescope system will be presented at the conference.

## II. MIRRORS

Like in MAGIC-I the parabolic tessellated reflector consists of about 250 individually movable  $1 \text{ m}^2$  mirror units, which are adjusted by the AMC depending on the orientation of the telescope. While in MAGIC-I each mirror unit consists of 4 individual spherical mirror tiles mounted on a panel, MAGIC-II is equipped with  $1 \text{ m}^2$  spherical mirrors consisting of one piece. This reduces cost and manpower because it is no longer necessary to align all four mirrors individual tiles inside one panel before installing the panels at the telescope.

Two different technologies have been used for the production of the  $1 \text{ m}^2$  mirrors. Out of the 247 mirror tiles, 143 are all-aluminum mirrors consisting of a sandwich of two 3 mm thick Al plates and a 65 mm thick Al honeycomb layer in the center. During production the sandwich is already bent into a spherical shape, roughly with the final radius of curvature. The polishing of the mirror surface by diamond milling is done by the LT Ultra company. Finally, a protecting quartz coating is applied. The reflectivity  $refl$  and the radius  $R_{90}$  of the circle containing 90% of the spot light have been measured to be around  $refl = 87\%$  and  $R_{90} = 3 \text{ mm}$ .

The remaining 104 mirror tiles are produced as a 26 mm tick sandwich of 2 mm glass plates around a Al honeycomb layer using a cold slumping technique. The frontal glass surface is coated with a reflecting Al layer and a protecting quartz coating. The glass-Al mirrors

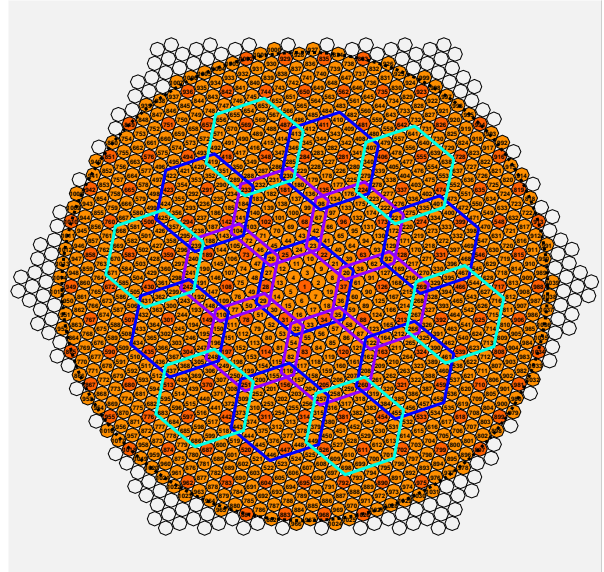


Fig. 2: A scheme of the MAGIC-II camera. Only colored pixels in a round configuration will be equipped. The hexagonal shapes indicate the trigger region, which is almost twice as large as the trigger region of the first telescope.

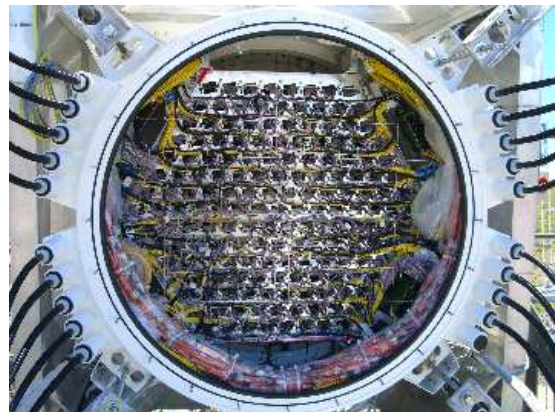


Fig. 3: A view of the MAGIC-II camera from the back shortly after its physical installation at the site and before plugging in the 7-pixel clusters. The 169 cluster modules are inserted from the camera front into the square holes which can be seen on the support metal plate. The pixel signals are transferred to the control house through optical fibers bundled inside the outer black cable ducts.

show a PSF which almost doubles ( $\sim 6 \text{ mm}$ ) that of the all-Al mirrors but the light spot is still well inside the size of a camera pixel.

## III. CAMERA

A modular design has been chosen for the camera of the MAGIC-II telescope [4]. Seven pixels in a hexagonal configuration are grouped to form one cluster, which can easily be removed and replaced. This allows easy exchange of faulty clusters. More importantly, it allows full or partial upgrade with improved photo detectors.

The 3.5° diameter FoV is similar to that of the MAGIC-I camera. The MAGIC-II camera is uniformly equipped with 1039 identical 0.1° FoV pixels in a round configuration (see figures II and II).

In the first phase increased QE PMTs have been installed. The Hamamatsu R10408 6 stage PMTs with hemispherical photocathode typically reach a peak QE of 34%. The PMTs have been tested for low afterpulsing rates, fast signal response ( $\sim 1$  ns FWHM) and acceptable aging properties.

Hamamatsu delivers PMT modules which include a socket with a Cockcroft-Walton type HV generator. The PMT socket and all the front-end analog electronics is assembled to form a compact pixel module. The broadband opto-electronic front-end electronics amplifies the PMT signal and converts it into an optical pulse, which is transmitted over optical fibers to the counting house.

A cluster consists of 7 pixel modules and a cluster body which includes common control electronics, power distribution and a test-pulse generator. On the front side the PMTs are equipped with Winston cone type light guides to minimize the dead area between the PMTs. The slow control electronics sets the pixel HV and reads the anode currents, the HV values and the temperature of each pixels. It is in turn controlled by a PC in the counting house over a custom made RS485 and VME optical link. The camera control software[5] is programmed in Labview and can be remotely steered by a central computer[8].

The calibration system of MAGIC-II[7] is based on a frequency tripled passively Q-Switched Nd-YAG laser, operating at the third harmonic at 355 nm, which has been installed in the center of the mirror dish. The pulse width at 355nm is 700ps. For providing a large dynamic range we are using two rotating filter wheels under computer control that allow one to illuminate the camera with intensities within 100 steps from single to 1000 photoelectrons. MAGIC-I will be equipped with a similar system in the next months.

The flexible cluster design allows field tests of this new technology within the MAGIC-II camera without major interference with the rest of the camera. The first test will in fact take place in the next months: it is planned to equip six 7-pixel modules in the outermost ring of MAGIC-II with HPDs [6] (at the corners of the hexagon in figure II which are not instrumented with PMTs). These HPDs feature peak QE values of 50%.

The smaller trigger area and somewhat lower light conversion efficiency of the first MAGIC telescope will limit the performance of the telescope system. This justifies a recent decision to upgrade the camera of MAGIC-I. The new MAGIC-I camera will be a clone of the camera of MAGIC-II, i.e., will have an increased trigger area and will be fully equipped with 0.1° FoV pixels. However its inner section (about 400 pixels) may be readily equipped with HPDs, i.e. the sensitivity of the new camera would significantly increase for low energy showers. The camera frame and electronics are already

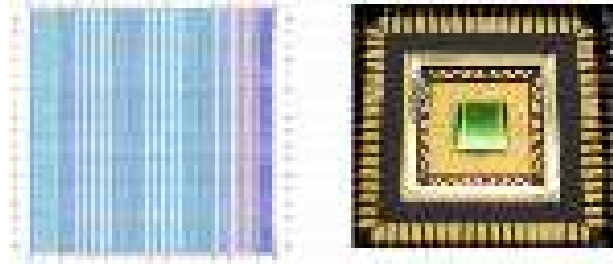


Fig. 4: Microphotograph of the Domino chip (left) and inside the package (right).

under construction. The readout will also be upgraded to a digitizing system similar to that of MAGIC-II (see below).

#### IV. READOUT

The optical signals from the camera are converted back to electrical signals inside the counting house[10]. The electrical signals are split in two branches. One branch is further amplified and transmitted to the digitizers while the other branch goes to a discriminator with a software adjustable threshold. The generated digital signal has a software controllable width and is sent to the trigger system of the second telescope with a software adjustable time delay. Scalers measure the trigger rates of the individual pixels.

The new 2 GSamples/s digitization and acquisition system is based upon a low power analog sampler called Domino Ring Sampler (see figure: 4). The analog signals are stored in a multi capacitor bank (1024 cell in DRS version 2) that is organized as a ring buffer, in which the single capacitors are sequentially enabled by a shift register driven by an internally generated 2 GHz clock locked by a PLL to a common synchronization signal. Once an external trigger has been received, the sampled signals in the ring buffer are read out at a lower frequency of 40 MHz and digitized with a 12 bits resolution ADC.

Data management is performed by 9U VME digital boards which handle the data compression and reformatting as well. Every board hosts 80 analog channels plus auxiliary digital signals for trigger and monitor purposes. For a 1 kHz trigger rate and a 2 GHz frequency sampling, the data throughput can be as high as 100 MBytes/s thus being a challenge for modern data transmission and storage solutions. The data are transferred to PCI memory via Gbit optical links using the CERN S-link protocol and to the mass storage system[11].

The MAGIC I telescope produces currently per year 100TByte of raw data that is calibrated and reduced on-site. Since 2007 most of the the data has been stored and further processed at the official MAGIC-II datacenter at PIC, Barcelona[12]. This datacenter is currently undergoing an upgrade to accomodate the even larger storage demands of MAGIC-II.

The newest version of the DRS chip (DRS version 4) features a number of advantages over DRS-2, so work is underway to upgrade the system in the next year to DRS-4.

## V. TRIGGER

The trigger system of the second telescope like the trigger of the first telescope[13] is based on a compact next neighbor logic. However, the uniform camera design allows an increased trigger area of  $2.5^\circ$  diameter FoV. This increases the potential to study extended sources and to perform sky scans.

When the two telescopes are operated in stereo mode a coincidence trigger (so-called “level 3” trigger) between the two telescopes rejects events which only triggered one telescope. In order to minimize the coincidence gate in the level 3 trigger, the triggers produced by the individual telescopes will be delayed in a time which depends of the geometry of the telescopes. This will reduce the overall trigger rate to a rate which is manageable by the data acquisition system.

Starting in 2007, an additional trigger runs in parallel with the standard next neighbour trigger in first telescope. This so-called “sumtrigger” [14] operates on the analog sum of groups of 18 pixels and has allowed to lower the trigger threshold of the MAGIC telescope by a factor of two to 25 GeV.

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