Extension of the Pierre Auger Observatory using high-elevation fluorescence telescopes (HEAT)

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***Abstract*. The original fluorescence telescopes of the southern Pierre Auger Observatory have a field of view from about 1.5° to 30° in elevation. The construction of three additional telescopes (High Elevation Auger Telescopes HEAT) is nearing completion and measurements with one telescope have started. A second telescope will be operational by the time of the conference. These new instruments have been designed to improve the quality of reconstruction of showers down to energies of 10^{17} eV. The extra telescopes are pivot-mounted for operation with a field of view from 30° to 58°. The design is optimised to record nearby showers in combination with the existing telescopes at one of the telescope sites, as well as to take data in hybrid mode using the measurements of surface detectors from a more compact array and additional muon detectors (AMIGA). The design, expected performance, status of construction, and first measurements are presented.**

***Keywords*: HEAT, high-elevation fluorescence telescope, galactic, extragalactic**

I. Introduction

The Pierre Auger Observatory has been designed to measure the energy, arrival direction and composition of cosmic rays from about 10^{18} eV to the highest energies with high precision and statistical significance. The construction of the southern site near Malargüe, Province of Mendoza, Argentina is completed since mid 2008 and the analysis of the recorded data has provided first results with respect to the energy spectrum [1], the distribution of arrival directions [2], the composition, and upper limits on the gamma ray and neutrino flux [3], [4]. The measured cosmic ray observables at the highest energies are suitable to tackle open questions like flux suppression due to the GZK cut-off, to discriminate between bottom-up and top-down models and to locate possible extragalactic point sources.

However, for best discrimination between astrophysical models, the knowledge of the evolution of the cosmic ray composition in the transition region from galactic to extragalactic cosmic rays in the range 10^{17} eV to 10^{19} eV is required. Tests of models for the acceleration and transport of galactic and extragalactic cosmic rays are sensitive to the composition and its energy dependence in the transition region where the current observatory has low efficiency.

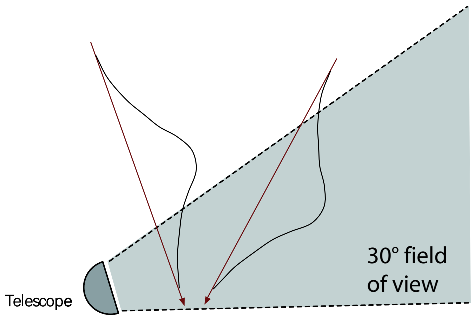

Fig. 1. Effect of limited field of view on reconstruction: Showers approaching the telescope have much higher reconstruction probability than those departing.

The fluorescence technique is best suited to determine the cosmic ray composition by a measurement of the depth of shower maximum. However, it is difficult to lower the energy threshold with the original design of the fluorescence telescopes. As the fluorescence light signal is roughly proportional to the primary particle energy, low energy showers can be detected only at close distance to a telescope. The field of view of the existing Auger fluorescence telescope (FD) is limited to 30° above the horizon (see figure 1). At close distances only the lowest few kilometres of the atmosphere are within the field of view. However, low energy showers reach their maximum of development at higher altitudes. Thus, the crucial region around the shower maximum is generally not observable. The small fraction of the shower development, which falls within the field of view, is mostly very dim and is insufficient to determine the depth of shower maximum $X_{\max}$. In addition, this cut-off effect also depends on primary mass and shower direction. A plain reconstruction of the shower profile using raw data would yield biased results with respect to zenith angle and mass composition. Cuts on the data to remove this bias (anti-bias cuts) are not useful as only very few showers would be left for the $X_{\max}$ determination.

From these arguments it is clear that an effective and unbiased detection of cosmic rays of lower energies requires the extension of the field of view to larger elevations. From the data collected since 2004, we know that the quality of reconstruction is improved considerably if showers are recorded by a hybrid trigger. These hybrid events provide information on the shower profile from the FD telescopes, but in addition at least one surface detector has detected secondary shower particles simultaneously. The data from the SD system restricts the time and the location of the shower impact point on ground. This improves the reconstruction of the shower geometry significantly [5]. An accurate geometry reconstruction with an uncertainty of about 0.5° is the necessary basis for energy and composition determination. But recording of hybrid data needs also adequate trigger efficiency for the individual surface detectors at lowest energies. Therefore, an enlarged energy range down to 10^{17} eV with high-quality hybrid events requires an extended field of view for FD telescopes in combination with a surface detector array of higher density in a small fraction of the observatory.

Fig. 2. Photo of the 3 HEAT telescopes tilted upward, end of January 2009. In the background the telecommunication tower of Coihueco is visible.

II. Design and properties of HEAT

In 2006 the Auger Collaboration decided to extend the original fluorescence detector, a system consisting of 24 telescopes located at four sites, by three High Elevation Auger Telescopes (HEAT). These telescopes have now been constructed, and they are located 180 m north-east of the Coihueco FD building. At the same time, the collaboration deployed extra surface detector stations as an infill array of 25 km^2 close to and in the field of HEAT. Additional large area muon detectors (AMIGA) [6] will determine the muon content of the shower and further improve the determination of the composition of the primary cosmic ray particles.

The design of HEAT is very similar to the original FD system, except for the possibility to tilt the telescopes upwards by 29°. In both cases a large field of view of about $30^\circ \times 30^\circ$ is obtained using a Schmidt optics. Fluorescence light entering the aperture is focused by a spherical mirror onto a camera containing 440 hexagonal PMTs. An UV transmitting filter mounted at the entrance window reduces background light from stars effectively. An annular corrector ring assures a spot size of about 0.6° despite the large effective aperture of 3 m^2. The high sensitivity of the Auger FD telescopes enables the detection of high energy showers up to 40 km distance. A slow control system for remote operation from Malargüe allows safe handling.

Differences between the conventional FD telescopes and HEAT are caused by the tilting mechanism. While the original 24 FD telescopes are housed in four solid concrete buildings, the 3 HEAT telescopes are installed in individual, pivot-mounted enclosures (see figure 2). Each telescope shelter is made out of lightweight insulated walls coupled to a steel structure. It rests on a strong steel frame filled with concrete. An electric motor can tilt this heavy platform though a commercial hydraulic drive by 29° within two minutes. The whole design is very rigid and can stand large wind and snow loads as required by legal regulations. All optical components are connected to the heavy-weight ground plate to avoid wind induced vibrations and to keep the geometry fixed.

Mirror and camera are adjusted in horizontal position. However, by tilting the telescope the varying gravitational force on camera body and mirror can change their relative position. Supplemental fixing bolts and an improved support structures are foreseen to keep the alignment of the optical system stable, which is essential for telescope pointing and optical resolution. Sensors for inclination are mounted at the mirror top, camera top and bottom, and at the aperture box. Distance sensors monitor the critical distance between camera and several points at the mirror system. These sensors are readout frequently for monitoring purposes.

Another design change for HEAT is the use of an improved DAQ electronics. The concept of the new electronics is the same as before, but as several electronic circuits have become obsolete, every front-end board had to be redesigned. Like the conventional FD electronics, the DAQ of one HEAT telescope contains 20 Analog Boards (AB) for analog signal processing, 20 First Level Trigger (FLT) boards for signal digitizing and storage, and one Second Level Trigger (SLT) board for the recognition of fluorescence light tracks and the initiation of data readout.

Along with faster FPGA logic the sampling rate was increased from 10 MHz to 20 MHz. The cut-off frequency of the anti-aliasing filters on the AB was adapted to about 7 MHz, but the other functions of the board remain the same. The redesigned FLT board implements all functions in FPGA of the Cyclone II FPGA family. A new custom-designed backplane provides dedicated point-to-point links between the FLT and SLT which lead to a factor 40 higher readout speed compared to the previous design. The usage of state-of-the-art FPGA in combination with the higher speed also establishes new fields of application for the DAQ system. The HEAT DAQ system is also the baseline design and the prototype for the Auger North FD electronics.

III. Operation of HEAT

The horizontal ('down') position is the only position in which a person can physically enter the enclosure. This configuration is used for installation, commissioning, and maintenance of the hardware. The absolute calibration of the telescopes will be performed in this position as well. As the field of view of the existing Coihueco telescopes overlaps with HEAT in down position, it is possible to record air showers or laser tracks simultaneously. By comparing the reconstruction results from both installations one can directly determine the telescope resolution in energy and $X_{\max}$. We also want to reserve part of the time at one HEAT telescope for prototype studies for Auger North. Recording the same event in Coihueco and with the Auger North prototype will allow a direct comparison of the trigger and reconstruction efficiencies.

The tilted ('up') position is the default HEAT state. Telescopes are moved into this position at the beginning of a measuring run and stay that way untill the end of the run. From the trigger point of view the telescopes operate like a fifth FD building. Data of of the different installations (HEAT, diffenent FD sites, infill and Amiga, surface detector) are merged offline only, but the exchange of triggers in real time makes the recording of hybrid showers possible. The combined data will improve the accuracy of shower energy and $X_{\max}$ determination at all energies, but especially at the lower end down to 10^{17} eV.

IV. First Measurements

First measurements were performed with HEAT telescope #2 at the end of January 2009. From January, 30^{th} to February, 1^{st} the telescope was operated for two nights in up and down position. At first, the camera was illuminated with a short light pulse from a blue LED located at the center of the mirror. The High Voltage for the PMTs and the individual electronic gains were adjusted to achieve uniform light response in every pixel. Subsequent measurements with the LED pulser were performed at different tilting angles, but with the same settings as found in in down position. No indications were found for a gain change due to changed orientation of the PMTs in the Earth's magnetic field.

In the next step, the mechanical stability of the optical system was verified. The telescope was tilted several times from down to up position and back. The readings of the inclination and distance sensors were recorded during the movement. The analysis of the distance between camera and center of the mirror showed damped oscillations of low amplitude which stopped within seconds after the movement terminated. At rest the distance change between up and down position is less than 0.5 mm which is neglible for the telescope's optical properties.

After these cross-checks several showers were recorded with the telescope tilted in up position and in coincidence with Coihueco telescopes #4 or #5. One of the recorded events is shown in figure 3. The event data of both telescopes match very well in time (colour of the pixels in figure 3). The reconstruction yields a shower distance of 2.83 ± 0.06 km from Coihueco and an energy of the primary particle of $(2.0 \pm 0.2) \cdot 10^{17}$ eV.

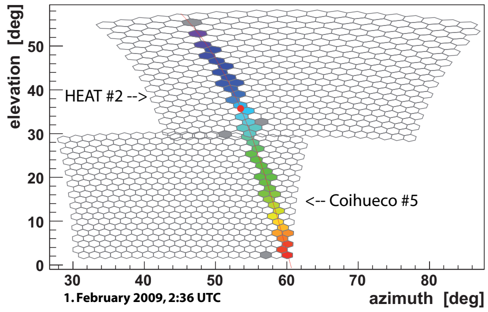

Fig. 3. This shower was recorded by HEAT telescope #2 and Coihueco telescope #5.The relative arrival time of the fluorescence light is coded in the colour of the pixel. The solid line is a fit of the shower detector plane.

In figure 4, the reconstructed longitudinal shower profile is shown together with a fit to a Gaisser-Hillas function. The fit yields a value of (657 ± 12) g cm^{-2} for $X_{\max}$. The plot also accentuates the need for HEAT telescopes for an accurate reconstruction: Using only the data point above a slant depth of 700 g cm^{-2} (Coihueco data) it would not have been possible to fit the profile and find a precise maximum.

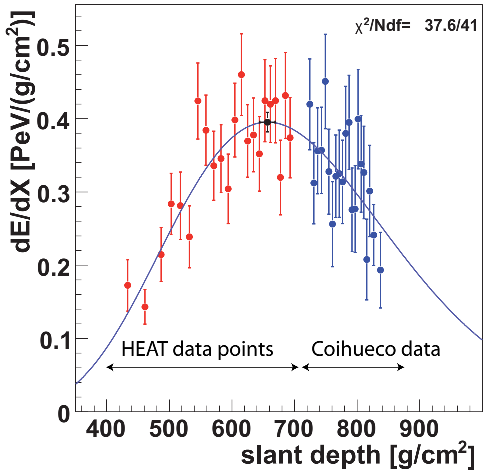

Fig. 4. Longitudinal shower profile of event in figure 3 together with Gaisser-Hillas-fit. Only a fit using both HEAT (left) and Coihueco (right) data points results in a reasonable $X_{\max}$ value.

V. Conclusion and Outlook

First measurements with a single telescope have demonstrated that HEAT will improve the energy threshold of the Pierre Auger Observatory at the Southern site down to about 10^{17} eV. The HEAT design satisfies all requirements with respect to stability and ease of operation. It is expected that all three HEAT telescopes are fully operational in September 2009. They will provide interesting data in the transition region from galactic to extragalactic sources and allow important prototype tests for the design of the Auger North FD system.

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