AMIGA, Auger Muons and Infill for the Ground Array

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Abstract: The Pierre Auger Observatory is planned to be upgraded so that the energy spectrum of cosmic rays can be studied down to 0.1 EeV and the muon component of showers can be determined. The former will lead to a spectrum measured by one technique from 0.1 EeV to beyond 100 EeV while the latter will aid identification of the primary particles. These enhancements consist of three high elevation telescopes (HEAT) and an infilled area having both surface detectors and underground muon counters (AMIGA). The surface array of the Auger Observatory will be enhanced over a 23.5 km^2 area by 85 detector pairs laid out as a graded array of water-Cherenkov detectors and 30 m^2 buried muon scintillator counters. The spacings in the array will be 433 and 750 m. The muon detectors will comprise highly segmented scintillators with optical fibres ending on multi-anode phototubes. The AMIGA complex will be centred 6.0 km away from the fluorescence detector installation at Coihueco and will be overlooked by the HEAT telescopes. We describe the design features of the AMIGA enhancement.

The cosmic ray spectrum shows three features at higher energies: the second knee, the ankle, and the GZK-cut off, and in order to seamless study this region [1] Auger will be upgraded with HEAT (High Elevation Auger Telescopes, [2]) and AMIGA (Auger Muons and Infill for the Ground Array). These two enhancements will encompass the second knee - ankle region where the transition from galactic to extra galactic cosmic rays is assumed to occur. The two main experimental requirements are good energy resolution in order to obtain the spectrum and primary type identification since the galactic (heavy primaries) to extra galactic (light primaries) source transition is directly linked to primary composition.

In this note we concentrate on AMIGA. It will consist of 85 pair of water Cherenkov surface detectors (SD) and 30 m^2 plastic scintillators buried $\sim$ 3.0 m underground, placed in a graded infill of 433 and 750 m triangular grids (see Fig. 1) overlooked by the fluorescence detectors (FD) (including HEAT) placed at the Coihueco hill top. AMIGA graded infilled areas are bound by the two hexagons shown in the figure covering areas of 5.9 and 23.5 km^2.

In regards to the mentioned spectrum measurement with good energy resolution, Auger hybrid detecting system was conceived in order to perform careful systematic uncertainty cross-checks which are currently under way. They will eventually permit to consolidate an energy spectrum of unprecedented precision. Main uncertainties in the energy calibration are the absolute calibration, the atmospheric light attenuation, and the fluorescence yield for the FD system, and the simulated airshower muon component for the SD system. There are clear indications that simulations under predict the shower muon contents [4] and as such the Auger SD energy estimator will be biased and this bias would increase with zenith angle [5]. Large muon counters will aid towards solving this problem by directly measuring the

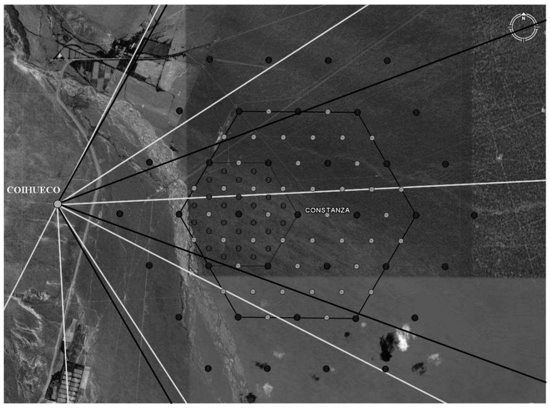

Figure 1: Layout of Auger enhancements. White and black lines show the six original and three enhanced telescopes FOVs, respectively. Grey, white and black dots indicate SDs plus buried muon counters placed 433, 750, and 1500 m apart, respectively. In this area a further enhancement of radio detection of extensive air showers will start its R&D phase [3].

number of muons with reduced poisson fluctuations.

In regards to composition analyses, the two relevant shower parameters are the atmospheric depth at shower maximum, X_{max}, and the shower muon contents. Other composition sensitive parameters dependent on them. Gamma-hadron discrimination is easier to perform than hadron-hadron discrimination since at E $\geq$ 0.1 EeV, X_{max} values for gamma induced showers are already well above those from hadron primary showers [6]. Also gamma showers are essentially electromagnetic with a vanishing muon component. No photon detection has been reported so far and a direct detection at E $\geq$ 1.0 EeV will encourage theoretical models such as correlations with nuclear primaries [7] and with super heavy dark matter decays ([6] and references within). In this latter supposition, an E $\geq$ 0.1 EeV gamma flux enhanced from the galactic center might be detected without a higher-energy counterpart. A further advantage of photon detection is that their sources are easier to identify since photons are not deflected by electromagnetic fields. Composition is very poorly understood in this energy range where a wide variety of mixed compositions are reported ranging from proton to iron dominated primaries ([8] and references within). Still, hadron composition can only be assessed within a given hadronic interaction model and much more robust results are attained from the variation rate of either X_{max} (the elongation rate) or muon contents as a function of energy [9]. A simultaneous change detected by both FD and muon counters will be the most compelling evidence of a composition change casting light on the transition of cosmic ray sources from galactic to extra galactic origins [10].

AMIGA reconstruction performances are quite encouraging, they have been outlined in [11, 10] for tank infilled areas and muon counters, respectively. Suffice to say that the surface detector reconstruction is currently well understood by the Auger collaboration and that we have developed [12] a detailed muon reconstruction system which is based on the parameterized muon lateral distribution function [13] currently used by KASCADE-Grande. The scintillator modules are simulated and the reconstruction procedure includes saturated (more than 90 muons) and silent (0,1, or 2 muons) counters. The shower reconstructed parameter is $N_\mu(600)$, the estimated number of muons 600 m away from the shower axis, an excellent primary type indicator.

In this note we are concentrating in the muon detector hardware. These counters will comprise highly segmented scintillators (to avoid under counting) with optical fibres ending on 64-pixel multi-anode photo multiplier tubes (PMT). The design adopts similar scintillator strips as for the MINOS experiment [14]. The current baseline design calls for 400 cm long $\times$ 4.1 cm wide $\times$ 1.0 cm high strips of extruded polystyrene doped with fluors and co-extruded with TiO_2 reflecting coating with a groove in where a wavelength shifter fibre is glued (see Fig. 2) and covered with reflective foil. Each module will consist of 64 strips with the fibres ending on an optical connector matched to a 64 multianode Hamamatsu H7546B PMT of 2mm $\times$ 2mm pixel size lodged in a PVC cas-

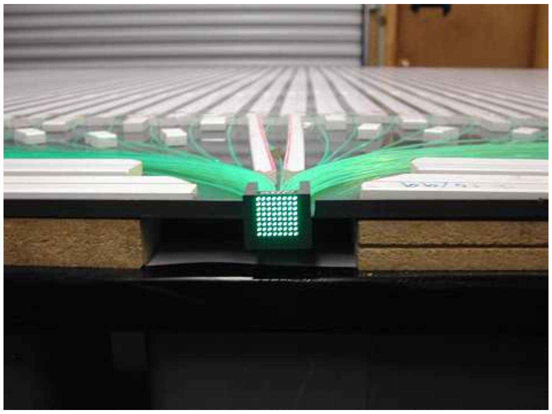

Figure 2: Muon counter assembly at Argonne National Laboratory of a 64 200 cm long prototype displaying the 64 pixel optical connector. The 4.1 cm wide strips and the green fibers are also shown.

ing. Each muon counter will be composed of three of these modules buried alongside a water Cherenkov tank, i.e. 192 independent channels.

The response of each scintillator strip will be characterized using a 5 mCu ^{137}Cs radioactive source mounted on a scanner designed for this purpose. The scanner is an X-Y positioning system with four tooth belt activated linear guides moved by two step-by-step motors of 8.7 Nm torque. The whole positioning system has up to 1 mm precision in any of the two axis and an effective total displacement of 5 m $\times$ 3.75 m. It will be mounted on a structure built of Rexroth (Bosch group) aluminum profiles which supports both the modules and the X-Y positioning system. This method has been validated by measuring ratios of collected charges and ratios of currents from scintillators strips with different optical fibers. The experimental layout consisted of three scintillator strips, each one with different wave length shifter optical fibers (Kuraray 1.0 mm, Kuraray 1.2 mm, and Bycron 1.2 mm) channelled to different pixels of a multianode PMT. Charges were collected from background muons impinging on the scintillators while currents were produced via a 20 μCu ^{137}Cs source mounted on top of the scintillators.

AMIGA electronics will have both an underground and a surface section powered by solar panels. Each of the three underground modules per counter will have attached a PCB with a data handling FPGA and a communication and monitoring system with a microcontroller. Each electronic channel will have an amplifier and a discriminator, set at $\sim 30\%$ of the pixel mean single photo electron amplitude. The pulses from all strips are synchronized to the 40 MHz water tank clock and after discrimination each strip output will either be 0 or 1. These numbers are stored in a circular buffer and upon reception of a tank trigger signal, they are adequately channelled by the microcontrollers to the surface electronics. On the surface, a second data handling FPGA receives the data and sends it to a microcomputer, which upon a request from the central data acquisition system at the Auger Campus, transmits both tank and muon counter data by radio link. Also, and in order to test each strip, a monitoring mode is envisaged by detecting atmospheric background muons.

AMIGA will communicate using an 802.11 standard wireless network, widely known as WiFi, taking advantage of the low cost and wide availability of this technology. As a plus, the high communication bandwidth will allow for the recollection of high amount of data at the early stages of the experiment, in order to study better the characteristics of muon counters and showers. This system must also be capable of carrying the surface detectors data and so the wireless local area network must integrate with the existing communications. The antennas and physical network topology are carefully chosen to cover long distances and avoid interferences. A two level star topology was chosen by setting concentrators relatively close to the subscriber stations. These concentrators are the center of four lower level logical stars (see Fig. 3) and they have a directional 120° sector antenna which collects the signal from the stations directional antennas. These stations use three 802.11 independent channels

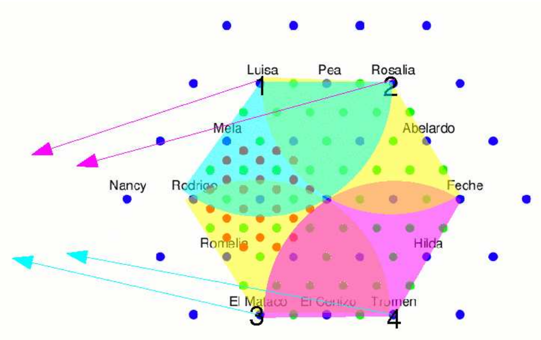

Figure 3: AMIGA two level telecommunication star topology. Concentrators are labelled from 1 to 4. In this layout concentrator-subscriber systems 2 and 3 use the same 802.11 independent channel. Bottom and upper arrows show channelling of data to the two access points.

E_o [EeV]	Area [km^2]	No. events year^{-1}
0.1	5.9	16000
0.3	23.5	8500

Table 1: Expected number of events per year with the AMIGA infilled areas.

but since there are four concentrators, one of these channels is used twice.

The higher level star is formed by two access points (AP) located at the Coihueco fluorescence observatory tower which collect the signal from the concentrators. Each AP will use an 802.11 independent channel, with two concentrators communicating to each channel. To minimize interference, the higher and lower levels stars will use different polarizations. Careful selection of the cell distribution and long range link paths must be made to further reduce interference.

An estimation of the number of events per year with energy larger than E_0 and zenith angle below $\theta_{max} = 60°$ was obtained by assuming a cosmic ray flux following a power law with spectral index -2.84 as quoted by Auger ([11] and references within), is displayed in Table 1.

AMIGA will start by deploying a prototype, after full commissioning of the 1500 m grid array which is planned to occur early 2008. This prototype will permit to gain experience on muon counters and experimentally estimate possible punch-throughs. It is designed to have three 4 m^2 X-Y parallel plates buried at three different depth, near the surface, at $\sim$ 3.0 m deep, and in between (this configuration might also shed some light on the muon momentum spectrum [5]). A unitary cell of seven detector pairs will be also deployed. This unitary cell will consist in detector pairs deployed $\sim$ 3.0 m underground at each vertex of a regular 750 m hexagon. These two prototype systems will be operated for one year prior to full deployment of the 750 m infill muon counters planned to start by mid 2009. The 750 infilled tank array will begin deployment simultaneously with the muon prototypes since this technology has been fully tested in Auger. The 433 m infill will start after completion of the 750 m infill.

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