Status And Perspectives Of The Pierre Auger Observatory

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Abstract

Cosmic ray research is at the energy forefront of astroparticle physics. Of particular interest are cosmic ray particles with energy $> 10^{20}$ eV. At such high energies the flux is very low and requires the use of very large detector fields. The Pierre Auger Observatory is being constructed to understand the nature and origin of these enigmatic particles. It will be the largest cosmic ray detector ever built, covering 3000 square kilometres in both hemispheres in its full configuration. The first runs have demonstrated a very good performance of the apparatus.

1. Introduction

In cosmic rays we find the highest-energy particles ever observed. Above energies of 10^{20} eV the protons, nuclei, or photons interact with various background radiation fields and should be strongly attenuated except if the sources are in our cosmological neighborhood (< 100 Mpc). Also protons of these energies may point back to the source and open a new kind of astronomy with charged particles. It is widely believed that cosmic rays up to some 10^{16} eV are of galactic origin, driven by stochastic acceleration in supernova explosions. It is speculated that the so-called ankle at 10^{18} eV may indicate the transition to a new, extragalactic component in cosmic rays. A compilation of experimental spectra at the highest energies is shown in figure 1; more recent results have been presented at this conference.

There are indications that the mass composition becomes lighter with increasing energy. There is no indication for gamma-ray induced events at 10^{20} eV. Inferences based on fluctuations of the depth of showers in the atmosphere should be taken with care; atmospheric variations may play a role here and were not accounted for so far.

The angular distribution of UHECR events is only known with insufficient statistics. At energies around 10^{18} eV the AGASA group reports an excess of

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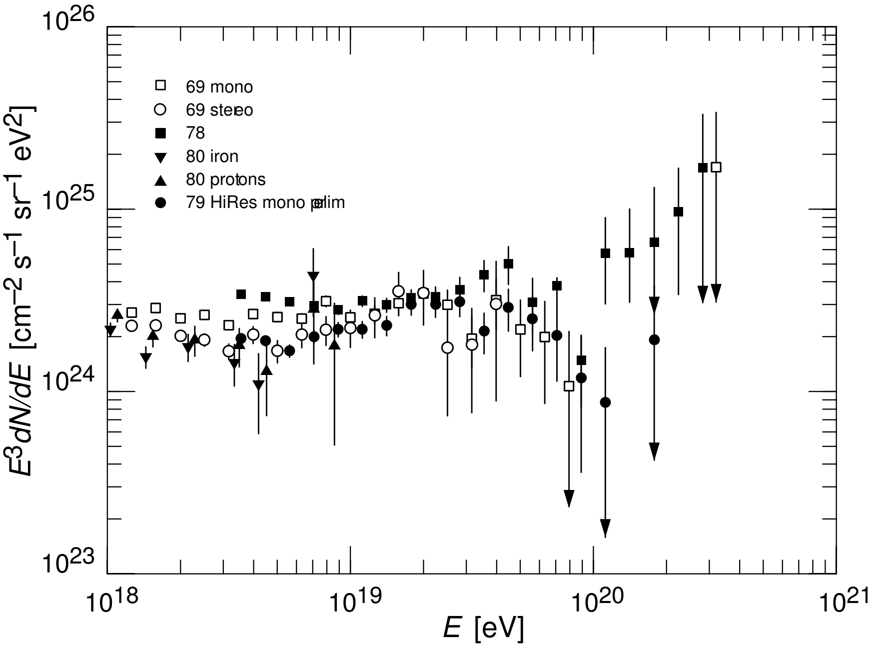


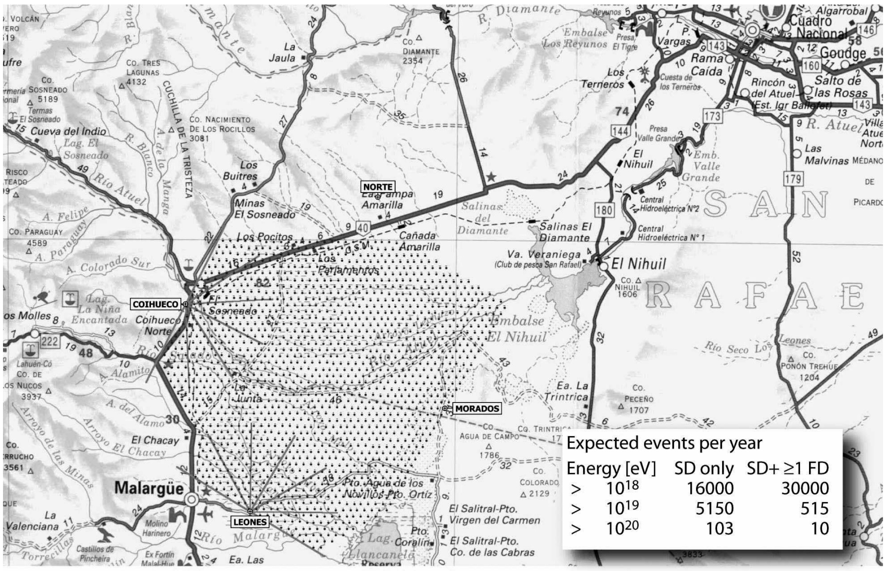
Fig. 1. Energy spectrum of cosmic rays taken from the Particle Data Group Review 2002. See [1] and references therein.

events coming from the galactic plane. At the highest energies there are some double or multiple events within the angular resolution but much more data are needed before strong conclusions can be made.

Large detectors for cosmic rays have also a significant detection potential for neutrinos, which may be distinguished from other primary particles as very inclined showers occuring deep in the atmosphere above the detector. The thickness of the atmosphere is $36,000 g/cm^2$ for a horizontal path (90 zenith angle) and only neutrinos can travel through most of this matter before they induce an extensive air shower near the detector. Neutrino-induced showers would exhibit a curved structure whereas ordinary, hadron-induced showers have a thin, flat muonic disk after traversing several atmospheric depths.

2. The Pierre Auger Observatory

The scientific objectives of the Pierre Auger Observatory are to understand the nature, origin and propagation of ultrahigh-energy cosmic rays. The questions addressed include: Are there point sources? Is there any evidence for anisotropies in the distribution of arrival directions? Does the energy spectrum exhibit a GZK-like suppression feature? What are the primary particles? What is the energy source acceleration or decays of supermassive relic particles? To answer these questions, the Auger Observatory is designed for full-sky coverage with an aperture of 7350 km^{2}sr in each hemisphere above 10^{19} eV, calculated for zenith angles up to 60°. Detailed information may be obtained from [2] and from the Pierre Auger Project internet portal [http://www.auger.org].



Expected events per year

Energy [eV]	SD only	SD+ ≥1 FD
> 10^{18}	16000	30000
> 10^{19}	5150	515
> 10^{20}	103	10

Fig. 2. Location and layout of the Southern Pierre Auger Observatory in Mendoza, Argentina. Each dot represents one water Cherenkov detector. The four telescope stations are placed on small elevations called LEONES, COIHUECO, MORADOS and NORTE. The fields of view for some telescopes are indicated. The inset gives the expected number of events per year for the full configuration assuming the AGASA energy spectrum.

The Pierre Auger Collaboration is a world-wide group of researchers from Argentina, Australia, Bolivia, Brasil, Czech Republic, France, Germany, Italy, Poland, Mexico, Slovenia, Spain, United Kingdom, USA and Vietnam. The full author list can be found at http://www.auger.org/auger-authors.pdf.

Construction of the Southern site started in 1999 in the Province of Mendoza, Argentina. The observatory campus is located in the city of Malargue at the South-West border of the detector field, see figure 2. The region of El Nihuil (35.2° S, 69.2° W, 1400 m.a.s.l., mean slope less than one percent) lies in the Province of Mendoza, 80 km west of San Rafael. In the final configuration 1600 water tanks will be placed on a triangular grid with 1.5 km spacing to cover 3000 km^2. Twenty-four fluorescence detectors in total will be grouped in four locations at the perimeter of the ground array to oversee the entire surface detector. This hybrid detection technique combines the statistical power of a ground array with calorimetric energy measurement and detailed longitudinal reconstruction for a

10% subset of showers recorded during clear, dark nights. The expected number of events above $10^{20} eV$ is about one hundred per year, if the spectrum continues with a slope suggested by the AGASA results. Using very inclinded showers, the Pierre Auger Observatory may detect neutrino fluxes at levels similar to that of the IceCube detector, but at higher energies [3-6].

The Surface Detector (SD) is made of water Cherenkov tanks. The tanks have 3.6 m diameter and 1.2 m height to contain 12 m^3 of ultra-clean water viewed by three 9" photomultiplier tubes (PMT). A solar panel and a buffer battery provide electric power for the local intelligent electronics, GPS synchronization system and wireless LAN communication. The abundant cosmic ray muons produce an essential calibration signal of about 80 photoelectrons in one PMT. The signals are continuously digitised with 16 bit dynamic range at 40 MHz sampling rate and temporarily stored in local memory. The time structure of PMT pulses carries rich information related to the mass of the primary particle. The trigger conditions will require four or five stations with a significant energy deposit. Detection efficiency will begin around 10^{18} eV and reach 100% at 10^{19} eV.

The Fluorescence Detector (FD) consists of 24 wide-angle Schmidt telescopes grouped in four stations, see Figure 1. Each telescope has a 30° field of view in azimuth and vertical angle. The four stations at the perimeter of the surface array consist of six telescopes each for a 180° field of view inward over the array. Each telescope is formed by segments to obtain a total surface of 12 m^2 on a radius of curvature of 3.40 m. The aperture has a diameter of 2.2 m and is equipped with optical filters and a corrector lens. In the focal surface a photomultiplier camera detects the light on 20×22 pixels. Each pixel covers $1.5° \times 1.5°$ and the total number of photomultipliers in the FD system is 13,200. PMT signals are continuously digitised at 10 MHz sampling rate with 15 bit dynamic range. The FPGA-based trigger system is designed to filter out shower traces from the random background of 200 Hz per PMT.

The track reconstruction in a stereo configuration or in a hybrid configuration together with a ground array is greatly improved compared to a monocular reconstruction. The detector is sensitive to the primary particle type exploiting the atmospheric depth in which the shower maximum occurs, the ratio of muons to electrons in the shower, and the time structure of the shower disk.

3. Results from the Engineering Array

An Engineering Array (EA) consisting of 40 water tanks and 2 prototype telescopes was built to demonstrate the hybrid concept and to validate the technical designs before mass production.

For the SD the construction and operation of the EA has allowed the testing of tanks (materials, liners, solar panels, brackets, cabling, etc.), as well as of the deployment strategy, water production and quality, photomultiplier tubes,

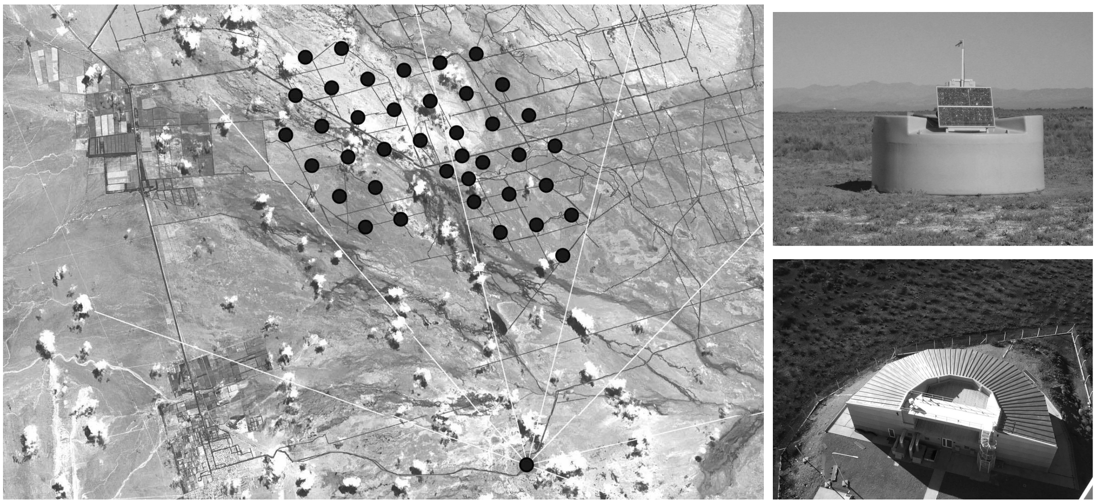


Fig. 3. Layout of the Engineering Array. Black dots are at the positions of water Cherenkov tanks. The black square is at the position of the first fluorescence detector station on the Los Leones hill. The white lines indicate the fields of view of the individual telescopes. Right: Photographs of a water Cherenkov detector in the field and of the Los Leones telescope building.

electronics, triggers, software and data acquisition, monitoring packages, telecommunications.

For the FD it has been possible to evaluate the performance of the optics, mirrors, electronics, corrector plates, filters and shutters with two prototype telescopes in the Los Leones building.

The location of the SD Engineering Array has its centre 10 km north of the FD building at Los Leones. Forty detector tanks were deployed, of which 32 were completely instrumented. 37 of these detectors were positioned on a triangular grid, covering an area of approximately $46km^2$. The mean and maximum position deviation of these tanks are 21m and 90m, respectively. Near the centre of this array, a further detector was placed 11m from an existing one. This pair of detectors enables comparisons of timing and density measurements to be made at essentially the same distance from the shower core. Additionally, two detectors were deployed at the middle of two of the triangles of the detector pair, i.e. at 860 m from their three nearest neighbours, allowing triggering on lower energy showers. The SD time synchronization using GPS works well within 50 ns and the angular resolution is the order of 1° or better. Figure 3 shows the geometry of the Engineering Array.

Photomultiplier calibration is carried out in three steps. Firstly, the three photomultiplier tubes are matched by gain by adjusting their voltages so that the rates (about 100 Hz) above a threshold of 3 vertical equivalent muons (VEM)

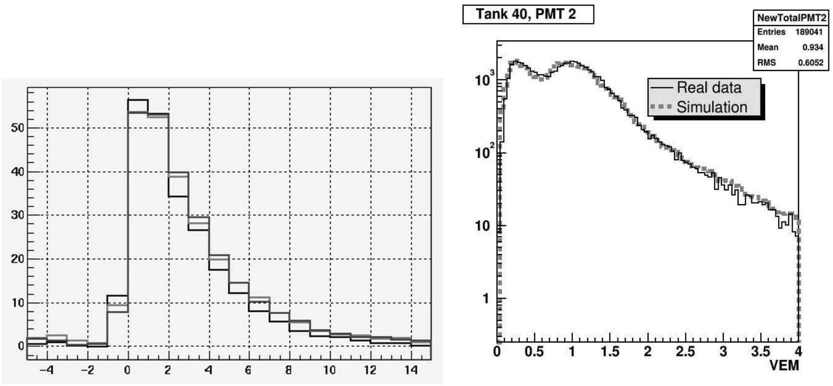


Fig. 4. Left: FADC muon traces for three photomultipliers in a tank; Right: total charge distribution on one photomultiplier. The peak at 1 VEM is due to single muons passing and forms the basis of the energy calibration.

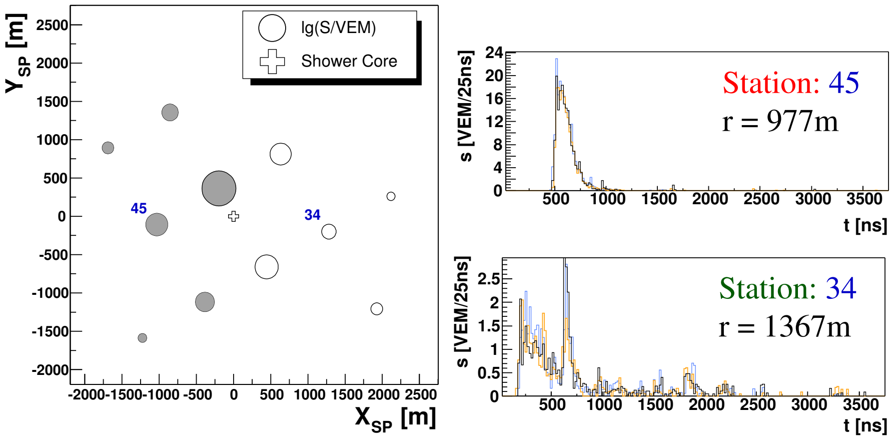
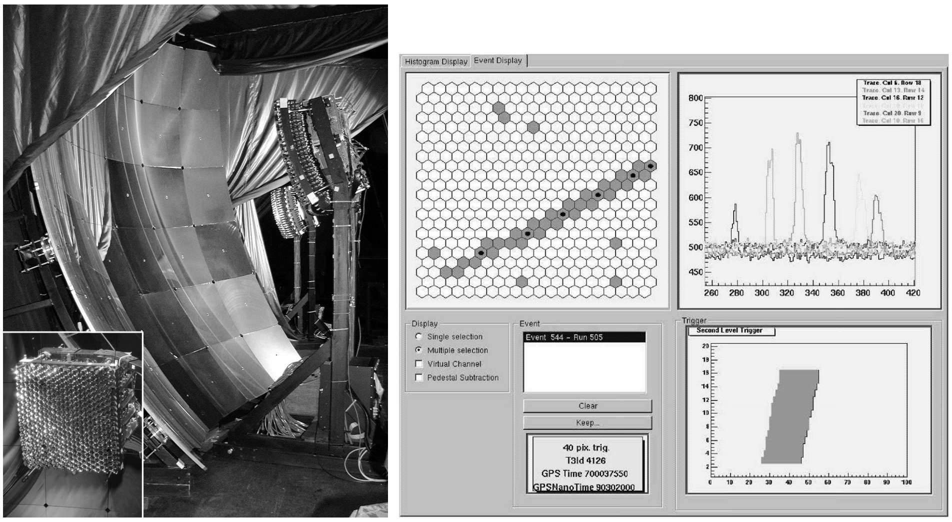


Fig. 5. Examples of events detected with the engineering array. Left panel: Particle densities projected into the plane perpendicular to the shower axis. The energy of this 11-tank shower is $(2-3)\cdot 10^{19}$ eV, the zenith angle is about 54°. Right panels: Close to the core substantial pulseheights are recorded; farther out, individual pulses from electrons (lower, wide-spread signals) and muons (sharp peaks) can be seen.

are the same. Secondly, the evolution of the gains is monitored and inserted into the data flow. Finally, the absolute calibration is determined from a sequence of measurements made on an identical test tank located at the central campus. Muons produced in the atmosphere provide the basis of the calibration chain. In addition to forming an extremely well-understood and uniform background across the whole of the surface array, the signal from a muon traversing a Cherenkov tank is proportional to the geometric path length. The calibration method therefore focuses on determining quantities related to the signals associated with muons. The peak due to single muons crossing the tank is clearly visible in a histogram of signals from a photomultiplier (figure 4). The position of this peak is an important calibration parameter.



○ Single selection
● Multiple selection
☐ Virtual Channel
☐ Pedestal Subtraction

Event 544 - Run 505

40 pix. trig.
T3Id 4126
GPS Time 700037550
GPSNanoTime 90302000

Fig. 6. Left: Photograph of a fluorescence telescope exhibiting the segmented mirror and the PMT camera. Right: online display of an event in the FD.

In figure 5 we show the geometry of an event recorded in the surface detector, together with two raw data FADC traces.

Part of the interior of the FD station Los Leones is shown in figure 6. The online event display shows a projection of the camera image; hit pixels are indicated on the camera (upper left panel) and raw FADC data are shown for selected pixels (upper right panel). The correct timing sequence of trigger channels is shown in the lower right panel.

Great attention is given to the atmosphere being an integral part of the fluorescence detector. The monitoring system uses laser beams, LIDAR, calibrated light sources and continuous recording of weather conditions. The fluorescence detectors were preliminary calibrated and atmospheric corrections were evaluated, including a subtraction of Cherenkov light, see figure 7. The sensitivity was estimated to be 10 EeV at 26 km distance. Using a YAG laser of adjustable pulse energy, we have verified that the FD meets the trigger sensitivity required to record $10^{19} eV$ showers throughout the SD aperture under normal atmospheric conditions.

The current signal coming from each phototube is sampled at 10 MHz with 12 bit resolution and 15 bit dynamic range. The First Level Trigger system performs a boxcar running sum of ten samples. The trigger is fired if the sum

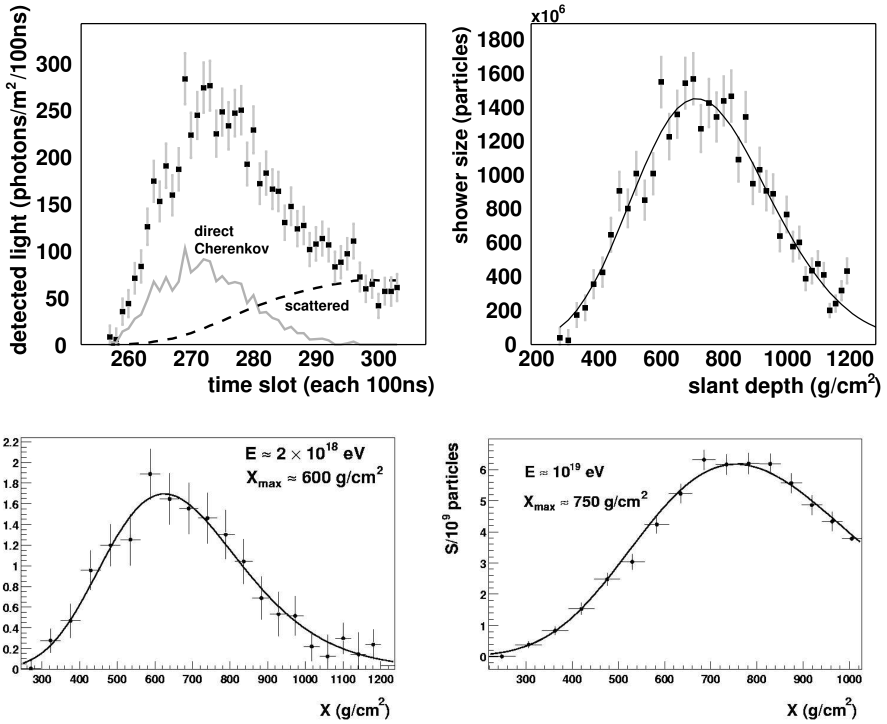


Fig. 7. Top: reconstruction of the fluorescence light curve subtracting the direct and scattered Cherenkov light (left) The right panel shows the final profile. Bottom: two other events seen by the fluorescence detector. The solid lines are fits to a Gaisser-Hillas curve.

exceeds a threshold . This threshold is determined by the trigger rate itself, and is regulated to keep it close to 100 Hz. Every microsecond, the camera is scanned for patterns of pixels that are consistent with a track induced by the fluorescence light from a shower. This is the Second Level Trigger, which had a rate of 0.3 Hz. It is dominated by muons hitting the camera directly and random noise. These components, as well as lightning, are then filtered by the software Third Level Trigger, yielding a rate of one event every 20 minutes per telescope. The two telescopes were operated during dark periods at 11% duty cycle as expected.

Special efforts are being made to determine the air fluorescence efficiency and its dependence on relevant conditions.

The ground array and fluorescence detectors were commissioned with the distributed, asynchronous data acquisition system from December 2001 onwards. During four months, the EA was operated continuously. It recorded several thousand events in either subsystem and about 70 hybrid events. As a final example of the successful initial operation of the Southern Auger Observatory we present in figure 8 a map of the arrival directions of 2500 events of all energies.

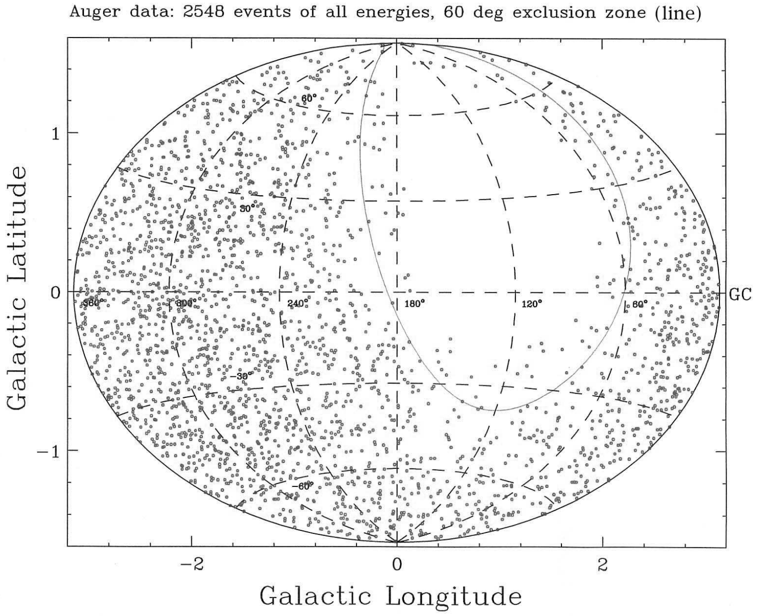
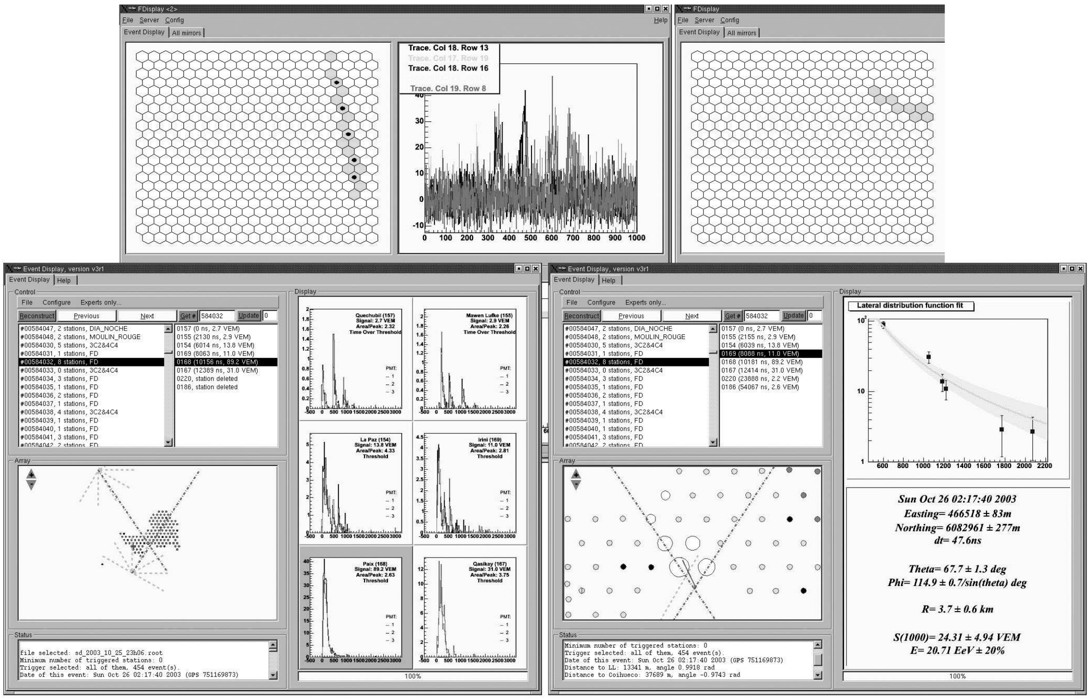


Fig. 8. Arrival direction distribution of the Auger EA events in galactic coordinates. The galactic centre is at the edge of the diagram. The line shows the exclusion zone for a zenith angle of 60 degrees.



```
#00584047, 2 stations, DIA_NOCHE
#00584048, 2 stations, MOULIN_ROUGE
#00584030, 5 stations, 3C2&4C4
#00584031, 1 stations, FD
#00584032, 8 stations, FD
#00584033, 0 stations, 3C2&4C4
#00584034, 3 stations, FD
#00584035, 1 stations, FD
#00584036, 2 stations, FD
#00584037, 1 stations, FD
#00584038, 4 stations, 3C2&4C4
#00584039, 1 stations, FD
#00584040, 1 stations, FD
#00584041, 3 stations, FD
#00584042, 2 stations, FD
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```
0157 (0 ns, 2.7 VEM)
0155 (2130 ns, 2.9 VEM)
0154 (6014 ns, 13.8 VEM)
0169 (8063 ns, 11.0 VEM)
0168 (10156 ns, 89.2 VEM)
0167 (12389 ns, 31.0 VEM)
0220, station deleted
0186, station deleted
```

```
file selected: sd_2003_10_25_23h06.root
Minimum number of triggered stations: 0
Trigger selected: all of them, 454 event(s).
Date of this event: Sun Oct 26 02:17:40 2003 (GPS 751169873)
```

```
0157 (0 ns, 2.7 VEM)
0155 (2155 ns, 2.9 VEM)
0154 (6039 ns, 13.8 VEM)
0169 (8088 ns, 11.0 VEM)
0168 (10181 ns, 89.2 VEM)
0167 (12414 ns, 31.0 VEM)
0220 (23888 ns, 2.2 VEM)
0186 (54067 ns, 2.6 VEM)
```

```
Minimum number of triggered stations: 0
Trigger selected: all of them, 454 event(s).
Date of this event: Sun Oct 26 02:17:40 2003 (GPS 751169873)
Distance to LL: 13341 m, angle 0.9918 rad
Distance to Coihueco: 37689 m, angle -0.9743 rad
```

```
Sun Oct 26 02:17:40 2003
Easting= 466518 ± 83m
Northing= 6082961 ± 277m
dt= 47.6ns

Theta= 67.7 ± 1.3 deg
Phi= 114.9 ± 0.7/sin(theta) deg

R= 3.7 ± 0.6 km

S(1000)= 24.31 ± 4.94 VEM
E= 20.71 EeV ± 20%
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Fig. 9. The first hybrid-stereo event recorded simultaneously in the fluorescence telescopes at Los Leones and Coihueco, and in several ground detectors.

4. Perspectives and Conclusion

The prototype apparatus has met or exceeded all our specifications. We are thus confident to proceed with the construction of the full-scale observatory.

Tanks are being deployed at a regular rate, filled with distilled water and electronic packages are installed rapidly. At the time of writing (November 2003) about 180 production tanks have been added to the Engineering Array. There are more than one hundred detectors operational now. Two buildings for fluorescence telescopes at LEONES and COIHUECO, indicated in figure 2, are completed and equipped with 4 and 2 telescopes of the final design, respectively. Hybrid operation of the surface array together with both the Los Leones and Coihueco telescopes has resumed, and first hybrid-stereoscopic events have been detected during October 2003, see figure 9.

Construction of a communications tower at the third location, Los Morados, and of this fluorescence building have started. The full configuration of the Southern site will be reached by 2005.

Full-sky coverage is important to interpret the expected data on ultra high-energy cosmic rays. The extreme cases are that point sources or an isotropic distribution will be found, with or without a GZK cut-off. The astronomical features of the Northern and Southern hemispheres are very different. Therefore, observations in one hemisphere cannot be extrapolated to the other one and a complete survey must be done. Thus, after completion of the Southern Auger Observatory, it is planned to commence construction of the Northern Auger Observatory. The selected site is in the USA in Millard County, Utah. An alternative site is in Colorado.

The Pierre Auger Observatory is starting up in a few years and will improve significantly our understanding of ultra-high energy cosmic rays.

5. References

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