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A large radio array at the Pierre Auger Observatory

Precision measurements of the properties of cosmic rays at the highest energies

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Abstract. The Pierre Auger observatory is presently being upgraded to enlarge its detection capabilities for ultra-high-energy cosmic rays. Part of this upgrade is a radio detector array, aimed to cover a surface area of 3000 km^2 to measure the properties of the highest-energy cosmic rays. The plans for this radio upgrade are outlined.

1 Introduction

The Pierre Auger Observatory, located in western Argentina, is the world's largest cosmic-ray observatory [1]. The objectives of the Observatory are to probe the origin and characteristics of cosmic rays above 10^{17} eV, the most energetic particles observed in nature, and to study their interactions. The Auger design features an array of 1600 water-Cherenkovdetector stations with 1500 m spacing spread over 3000 km^2 and overlooked by 24 air fluorescence telescopes. In addition, three high-elevation fluorescence telescopes overlook a 23.5 km^2, 61-detector infilled array with 750 m spacing. Radio emission from extensive air showers is measured with the Auger Engineering Radio Array (AERA), comprising more than 150 radio detector stations, covering an area of about 17 km^2 [2], colocated with the infill array.

Recent scientific highlights from the Observatory include the observation of a dipole in the arrival direction of cosmic rays with energies exceeding $8 \cdot 10^{18}$ eV [3]. A dipole has been measured with an amplitude of 6.5% with a significance of more than 5.2 σ. Another highlight is the follow-up of a gravitational wave event (GW170817), looking for high-energy neutrinos with the Auger observatory [4, 5]. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. The non-detection is consistent with model predictions of short GRBs observed at large off-axis angles. Core tasks of the observatory are to measure the energy spectrum and mass composition of cosmic rays at the highest energies (e.g. [6]).

At present, the Pierre Auger collaboration is working on an upgrade of the Observatory (Auger Prime). The physics case of the upgrade is outlined in [7]. The *key science questions* to be addressed

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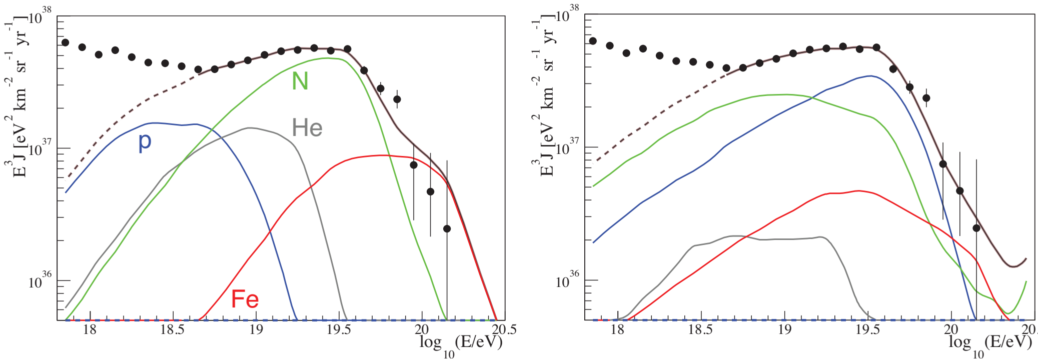

Figure 1. Examples of fluxes of different mass groups (as indicated) for describing the Auger spectrum and composition data [7]. Two scenarios are shown: particles being accelerated up to a maximum rigidity (left) and particles undergoing photo-disintegration during propagation (right).

are: What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)? Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale? What are the fractions of protons, photons, and neutrinos in cosmic rays at the highest energies?

A key to understand the origin of the highest-energy cosmic rays is to precisely measure the elemental composition up to the highest energies (10^{20} eV and above). Two baseline scenarios are illustrated in Fig. (1), showing the expected energy spectra for elemental groups. The left-hand side illustrates expectations for a scenario in which cosmic rays are accelerated up to a maximum rigidity. The elemental groups exhibit fall-offs at energies proportional to their elemental charge Z. The right-hand side shows an expectation for particles undergoing photo-disintegration during propagation. In this scenario a significant fraction of light particles (protons) is expected even at the highest energies, this is the main difference to the maximum rigidity scenario, in which heavier particles (large Z) are expected at the highest energies.

To achieve these objectives, a layer of scintillators is installed above the water-Cherenkovdetectors, the observation time of the fluorescence detectors is being increased, and underground muon detectors are being installed in a part of the Surface Detector array. In addition, radio antennas will be added to each Surface Detector station as described below.

2 Radio detection of (horizontal) air showers

The radio emission from extensive air showers [8–10] is investigated at the Auger observatory with AERA [11]. Radio emission is detected in the frequency range from 30 to 80 MHz [12]. The antenna response is calibrated with a reference source in-situ at the observatory in the field [13]. Timing calibration is performed with a reference transmitter and using radio pulses emitted from commercial airplanes [14]. A resolution of better than 2 ns has been achieved.

Measurements of the polarization of the radio signals allows one to have a closer look at the emission processes of the radiation in the extensive air showers [15]. The majority of the emission in the atmosphere is found to be due to the interaction of the shower with the geomagnetic field (transverse separation of charges, geomagnetic effect) [16]. Of the order of 15% of the radiation is due to the longitudinal separation of charges (Askaryan effect) [17].

The measurement of the radio footprint of an air shower yields a precise determination of the shower energy [18, 19]. A cosmic ray with an energy of 1 EeV delivers about 15.8 MeV of energy to

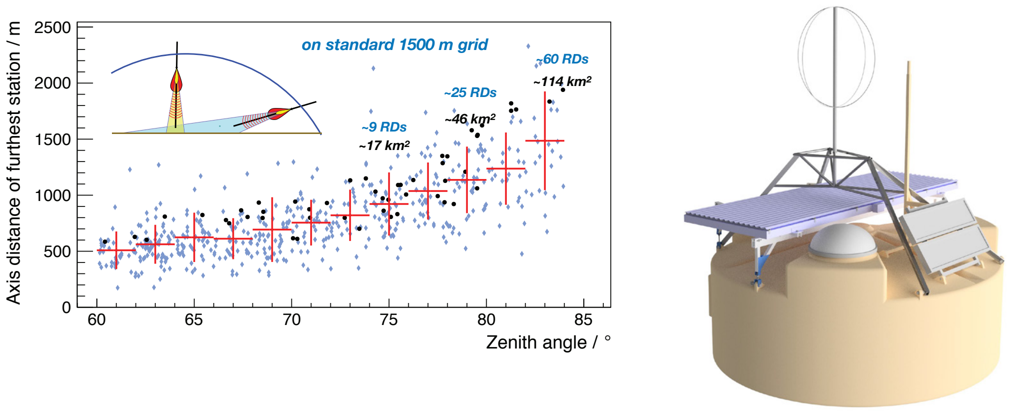

Figure 2. Left: Furthest axial distance at which a radio signal above noise background has been detected with AERA as a function of the air-shower zenith angle. **Right:** Conceptional illustration of an upgraded station of the Surface Detector array of the Pierre Auger observatory, comprised of (from bottom to top) a water-Cherenkovdetector, a layer of scintillators (Surface Scintillator Detector), and a radio antenna (Radio Detector).

the ground in the frequency range from 30 to 80 MHz. The radio emission measured on the ground $E_{30-80\ \mathrm{MHz}}$ can be used to establish an absolute calibration of the energy scale E_{CR}, using the universal formula

$$E_{30-80\ \mathrm{MHz}} = [15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst})]\ \mathrm{MeV} \times \left(\sin\alpha \frac{E_{\mathrm{CR}}}{10^{18}\ \mathrm{eV}} \frac{B_{\mathrm{Earth}}}{0.24\ \mathrm{G}}\right)^2, \tag{1}$$

knowing the magnetic field B_{Earth} at the location of the detector and the angle α between the direction of the Earth magnetic field and the direction of the air shower.

AERA has also been used to measure radio emission from air showers with zenith angles between 60° and 84° ("horizontal air showers") [20, 21]. The size of the radio footprint of an air shower has been measured at large zenith angles. The distance from the shower axis to the furthest radio detector (in the shower plane, perpendicular to the shower axis) is depicted in Fig. (2) (left) as a function of the zenith angle of the air shower. In the figure also the expected number of radio stations (on the standard Auger 1500 m grid) with a signal above threshold is indicated together with an estimate of the size of the footprint on the ground. As can be seen, for horizontal air showers (i.e. large zenith angles) the footprints reach sizes exceeding tens of km^2 and dozens of stations will have a signal above threshold. This is a very important result since it confirms experimentally that the radio emission from horizontal air showers can be measured with radio antennas on the standard Auger 1500 m grid.

3 The Auger radio upgrade

We plan to install a radio antenna on each of the 1661 stations of the Surface Detector array of the observatory, forming a 3000 km^2 radio array, the largest radio array for cosmic-ray detection in the world. An artists impression of the planned set-up is given in Fig. (2) (right). It shows (from bottom to top) the water-Cherenkovdetector with a layer of scintillators on top (Surface Scintillator Detector) and a radio antenna (Radio Detector). The concept of radio antennas on top of the Surface

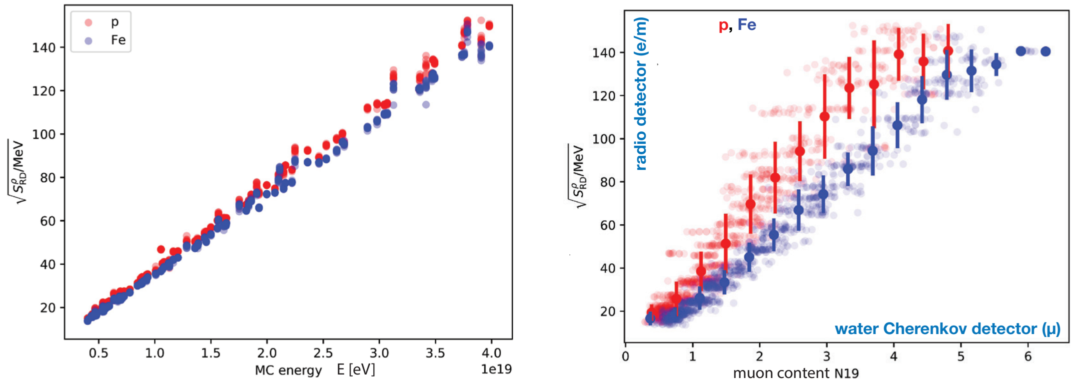

Figure 3. Estimated performance of the Radio Detector. PRELIMINARY RESULTS; The detector resolution of the Radio Detector is not yet included. **Left:** radiation energy (i.e. the electromagnetic energy of the shower) as a function of the shower energy. **Right:** electromagnetic energy in a shower as measured by the Radio Detector as a function of the muon content in a shower as measured by the water-Cherenkovdetector.

Detector stations has been studied earlier at the Auger observatory on smaller scales [22]. With the combination of water-Cherenkovdetector and Surface Scintillator Detector the electron-to-muon ratio (e/μ) is measured for vertical showers. In a similar way the combination of water-Cherenkovdetector and Radio Detector will be used to measure the e/μ ratio for horizontal air showers. In turn, the e/μ ratio will be used to derive the particle type of the incoming cosmic ray up to the highest energies. This is the main goal of the Auger upgrade, to measure the particle type of each incoming cosmic ray. The radio upgrade will increase the aperture of the observatory for mass-sensitive investigations, allowing e/μ separation for showers with a broad zenith angle range, from zenith with the Surface Scintillator Detector to the horizon with the Radio Detector.

There is an important difference related to the mass measurement of cosmic rays at AERA (for vertical showers) and the radio upgrade (for horizontal air showers). For vertical showers we use a geometrical method, correlating the size of the footprint on the ground to the distance from the observer to the shower maximum. From this quantity, the depth of the shower maximum $X_{\max}$ is derived, which in turn is dependent on the logarithm of the number of nucleons A of the incoming cosmic ray $X_{\max} \propto \ln A$ [2]. For horizontal showers we aim to apply a different method: We will use a combination of radio antennas and the water-Cherenkovdetectors to measure the e/μ ratio in air showers to determine $\ln A$.

Increasing the mass sensitivity of the observatory is crucial to understanding the origin of cosmic rays, e.g. a good mass sensitivity is needed to distinguish between the baseline scenarios illustrated in Fig. (1). Precise mass (and charge Z) information will also allow the construction of more meaningful sky maps using intervals of rigidity E/Z in place of energy E (as done so far). Isolating particles with a small (or no) charge such as protons, neutrinos, and gamma rays is important to conduct astronomy with such particles at energies exceeding EeV energies. This will give direct hints to the cosmic-ray sources. Finally, the Radio Detector will provide a clean measurement of the electromagnetic (e/m) component of the air showers. This is of interest to study shower physics in the atmosphere. In particular, in the densely populated part of the Surface Detector array [7], we will have water-Cherenkovdetectors and Surface Scintillator Detectors with a 750 m spacing, underground muon detectors (AMIGA) and also radio antennas. We will have a clean measurement of the e/m component from the Radio Detector and a clean measurement of the muons with AMIGA. This will allow to cross check the unfolding of the e/μ ratio with the Surface Scintillator Detector-

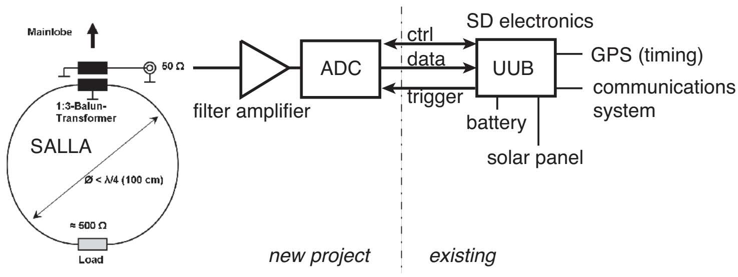

Figure 4. Schematic view of the envisaged read out for the radio antennas. The radio antenna (here illustrated as "SALLA") is read out through a filter amplifier and an ADC. The front end board has an interface to the existing electronics (UUB) at each Surface Detector station.

water-Cherenkovdetector combination, based on measured showers. Last but not least, the Radio Detector will provide an independent mass and energy scale to cross check the Surface Scintillator Detector-water-Cherenkovdetector results.

In a first analysis the **physics potential** of the radio upgrade has been studied using CORSIKA[23]/CoREAS[24] simulations. 192 showers have been simulated with energies from 4 to 40 EeV and zenith angles between 60° to 80°. Half of the showers were induced by protons, the other half by iron nuclei. A full water-Cherenkovdetector simulation and reconstruction has been included in the analysis, but only a simplified treatment of the radio signals was available. The normalized radiation energy has been calculated as described in [25]. The radiation energy has been "smeared out" in order to mimic reconstruction uncertainties. PRELIMINARY results are illustrated in Fig. (3). The left-hand panel depicts the detected radiation energy as a function of the shower energy. A clear correlation can be seen and only a small dependence on the mass of the incoming cosmic rays (represented in the figure through the extrema protons and iron nuclei). The mass-sensitivity is illustrated on the right-hand side. The size of the e/m component (as measured with the Radio Detector) is plotted as a function of the muon number (as obtained with the water-Cherenkovdetector). A clear separation between showers induced by protons and iron nuclei is visible. Please note: the flattening at the top-right is due to a technical flaw in the simulations, only showers up to a certain (too low) energy have been simulated. This is work in progress. We are working on more precise simulation studies in order to quantify various properties of the radio upgrade such as mass resolution, energy resolution, effective aperture as a function of energy, etc.

At present we are working on the details of the **technical implementation** of the radio upgrade. The Radio Detector will be fully integrated in the Surface Detector stations, they will form one unit, being comprised of water-Cherenkovdetector, Surface Scintillator Detector, and Radio Detector. The different detectors will share the infrastructure such as solar power, battery, communications system, GPS timing, and an integrated data acquisition system. The envisaged system is schematically shown in Fig. (4).

We aim to use a short aperiodic loaded loop antenna (SALLA) to detect the radio emission from air showers in the frequency range 30 to 80 MHz. The antenna response has been characterized in field measurements [12] and about 60 of such antennas are already used at the Tunka site to measure air showers [26]. The water-Cherenkovdetector will issue a trigger signal when an air shower has been detected. The data from the radio antenna will be passed to the read-out electronics of the Surface Scintillator Detector/water-Cherenkovdetector system (UUB) and will be transmitted together with all data from the station to the central data acquisition of the Auger observatory.

A schematic view of the radio front-end board is depicted in Fig. (5). We foresee two polarization directions of the antenna, oriented orthogonal to each other (see also Fig. (6)). The signals of the two analogue channels will be pre-amplified in a Low-Noise Amplifier (LNA) at the antenna. The signals are transmitted through shielded coaxial cables to the filter amplifier on the front-end board. They

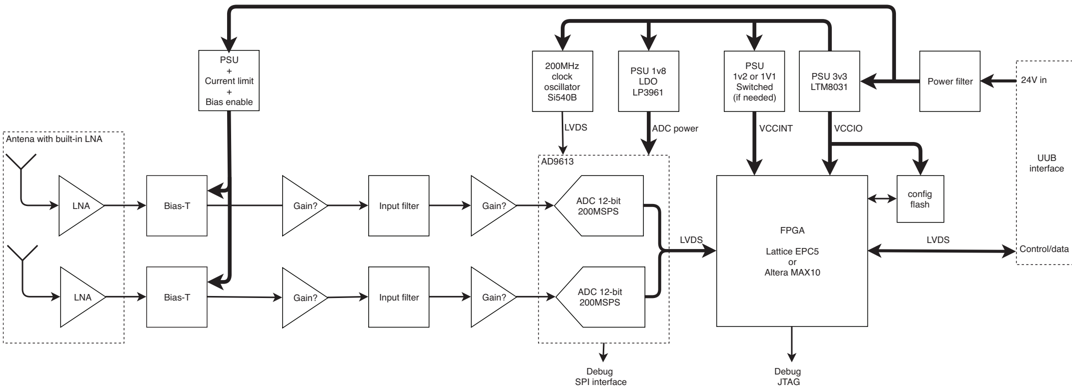

Figure 5. Block diagram of the front end board for the Radio Detectors (draft – work in progress).

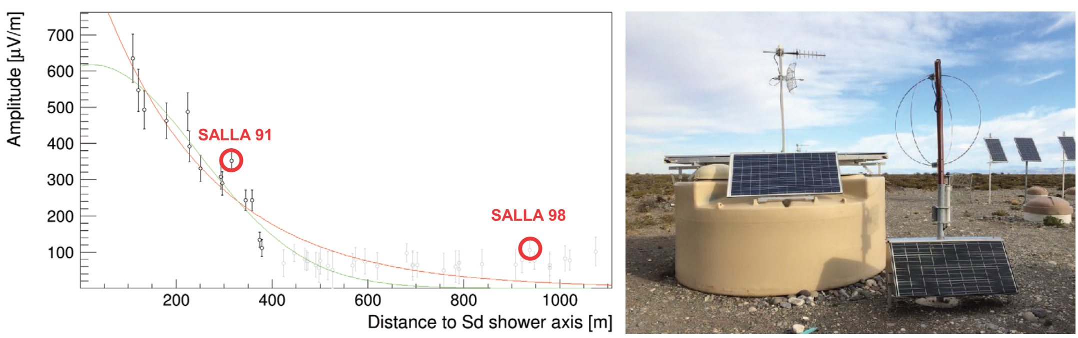

Figure 6. Left: Lateral distribution function of the radio emission from an air shower as measured with AERA and two prototype antennas (indicated as "SALLA"). **Right:** a prototype Radio Detector station (front, right) at a Surface Detector station of the Pierre Auger observatory with a scintillator module on top of a water-Cherenkovdetector.

will be digitized with a sampling frequency of 200 Msps. A FPGA controls the data flow and the communication with the existing electronics of each Surface Detector station (UUB).

To test the performance of the SALLA antennas we have installed three prototype stations inside the AERA field at the Auger observatory. Such a prototype station is shown in Fig. (6) (right); An AERA station with SALLA antenna is situated next to a water-Cherenkovdetector with Surface Scintillator Detector module on top. The first air showers have been measured in coincidence with the prototype stations. As an example, the lateral density distribution of the radio signal for a measured air shower is presented in Fig. (6) (left). The signals from the SALLA antennas are compared to the "regular" AERA stations. The signals measured with the SALLA antennas are slightly bigger, due to a preliminary calibration used for the SALLA antennas.

Our **timeline** for the installation of the radio upgrade at the Auger observatory is as follows. We are presently working on the details of the technical implementation. We aim to conclude this throughout the year 2019. We envisage to start the mass production of the detector components in the second half of 2019 and are looking forward to deploying the detectors in the field in 2020.

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