Radio detection of cosmic rays with the Auger Engineering Radio Array

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Abstract. The Auger Engineering Radio Array (AERA) complements the Pierre Auger Observatory with 150 radio-antenna stations measuring in the frequency range from 30 to 80 MHz. With an instrumented area of 17 km^2, the array constitutes the largest cosmic-ray radio detector built to date, allowing us to do multi-hybrid measurements of cosmic rays in the energy range of 10^{17} eV up to several 10^{18} eV. We give an overview of AERA results and discuss the significance of radio detection for the validation of the energy scale of cosmic-ray detectors as well as for mass-composition measurements.

1 Introduction

The Pierre Auger Observatory [1] exploits hybrid detection of extensive air showers measured at the same time with multiple detection techniques for optimum determination of the energy and mass of cosmic ray primaries. Following this spirit, its baseline surface detector (SD) and fluorescence detectors (FD) have been complemented by an array of radio detectors. This Auger Engineering Radio Array (AERA) was deployed in the region where many enhancements, focused in particular at the detection of air showers with energies in the EeV energy regime, have been set up.

In this article, we briefly review the characteristics and capabilities of the radio detectors of the Pierre Auger Observatory and discuss how they contribute valuable information in particular for the determination of the energy scale of cosmic rays as well as mass composition studies.

2 The Auger Engineering Radio Array

When work on AERA began in 2008, the nature and characteristics of the radio emission from extensive air showers were still largely unclear — unlike today, where the emission physics and signal characteristics are very-well understood [2, 3]. Furthermore, many questions regarding the best strategy for the measurement of these pulsed radio signals were still open. The goal of AERA, illustrated by the explicit mentioning of "engineering" in its name, was to explore different options for implementing a radio detector that can be scaled to areas significantly larger than a km^2.

These efforts resulted in the setup of a 17 km^2 array of radio detectors. The individual detector stations are *autonomous* and can thus be freely spaced. Many of the ex-

perimental challenges, for example related to power supply, communications and data acquisition, were indeed related to this autonomous design, which is a key and unique feature of AERA that differentiates it from purely cabled setups for radio detection of cosmic rays.

The layout of the array is depicted in Figure 1. The radio antennas are co-located with the 750 m surface detector array, the Coihueco and HEAT fluorescence telescopes, and the AMIGA underground muon detectors. This combination of detectors at the same location maximizes the information gathered on each individual air shower by multi-hybrid detection.

The antennas have been set up on a graded array, with grid constants of 144, 250, 375 and 750 meters, probing different energy and zenith angle ranges. Two different types of antennas, Logarithmic Periodic Dipole Antennas (LPDAs) [4, 5] and "butterfly antennas" [4] are in use. Both measure in the frequency band from 30 to 80 MHz. Furthermore, two different types of digital electronics, both of them capable of "internal" triggering on radio signals and one of them, in addition, allowing data buffering for up to 8 seconds and thus exploitation of external triggering by the SD and FD, have been developed and deployed. A reference "beacon" transmitter is used to achieve time synchronization of the autonomous detectors within two nanoseconds [6].

AERA started taking data in 2011 and has been finalized in its current form in 2015. Its current dataset encompasses more than 10,000 extensive air showers measured with both the SD and the radio antennas. In the following, we give a concise overview of the most important results derived with AERA up to now.

3 Determination of the cosmic-ray energy

One of the key parameters to characterize cosmic-ray primaries is their energy. With AERA, we have demonstrated

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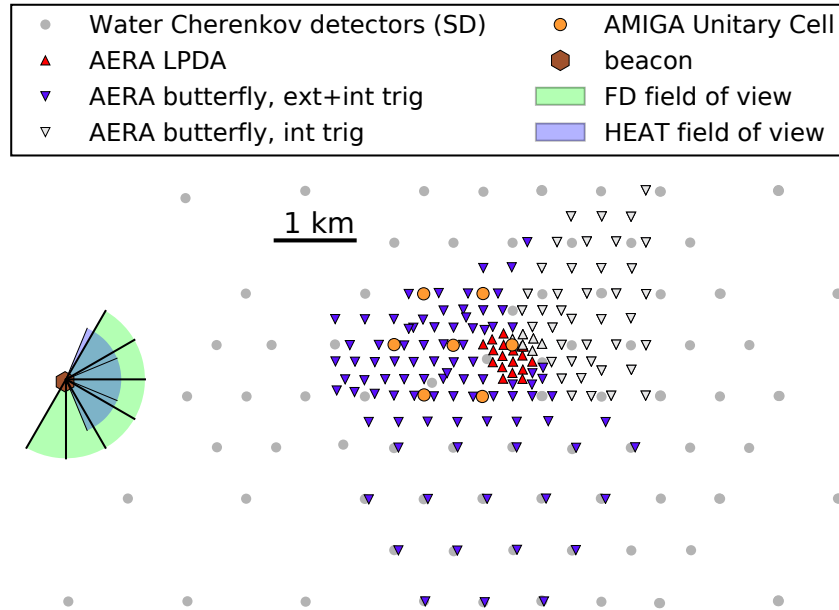**Full author list at http://www.auger.org/archive/authors_2018_10.html

Figure 1. Map of the Auger Engineering Radio Array. 150 radio-detector stations cover a total area of 17 km^2. Further explanations are given in the text.

that this energy can be determined with a resolution of 17% or better [7]. Many different approaches exist to determine the cosmic-ray energy from radio measurements [2]. In AERA, we determine the *energy fluence*, i.e. the energy deposited in the form of radio signals per unit area, at the locations of our radio detector stations. Exploiting our knowledge of the radio-emission pattern, we can then interpolate and finally integrate the energy fluence to determine the total energy deposited on the ground in the form of radio signals, the *radiation energy*.

After correction for the orientation with regard to the geomagnetic field, this radiation energy is closely correlated with the energy in the electromagnetic cascade of the air shower, following a quadratic scaling because of the coherent nature of the radio emission. This is shown in Figure 2. As the radio emission undergoes no significant absorption or scattering in the atmosphere and constitutes a calorimetric quantity, it is very well suited for cross-calibration of cosmic-ray detectors via radio measurements [8]. Comparing the measured radiation energy to the one predicted by first-principle Monte Carlo simulations [9] also provides the opportunity for an independent cross check and validation of the energy scale of the Pierre Auger Observatory [10], which is based on measurements of the fluorescence detectors.

4 Mass composition sensitivity

The depth of maximum $X_{\max}$ of an extensive air shower is a mass-sensitive parameter that is directly accessible with fluorescence measurements. Radio signals from air showers also have sensitivity to $X_{\max}$ due to the forward-beamed nature of the emission as well as its enhancement on a Cherenkov ring introduced by the non-unity refractive index of the atmosphere [2]. Deeper showers thus produce a
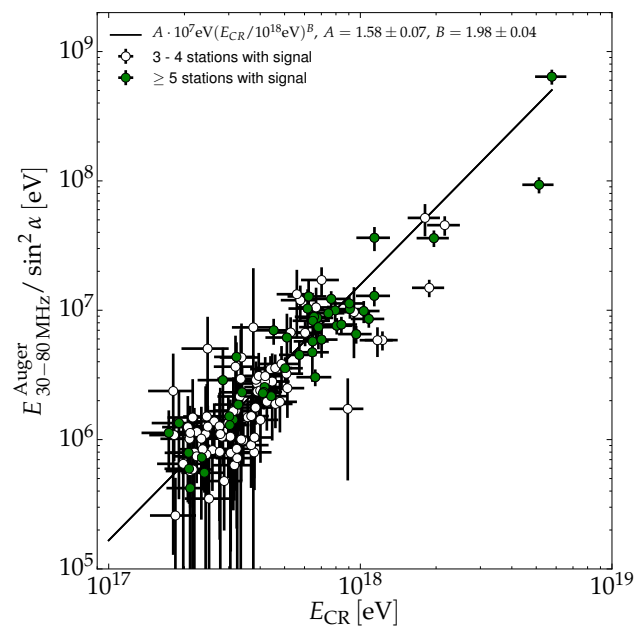

Figure 2. After correction for the angle of incidence with respect to the geomagnetic field α, the energy deposited on the ground in the form of radio signals, the *radiation energy*, scales quadratically with the energy of the primary cosmic ray. With AERA, an energy resolution of 17% has so far been demonstrated [8] for events detected in at least 5 radio-detector stations with signal.

steeper signal falloff with lateral distance from the impact point than shallower showers. In addition, pulse shape and polarization information can be exploited.

We have demonstrated that by comparison of the radio signals of measured air showers with per-event Monte Carlo simulations, $X_{\max}$ can be determined and is in agree-
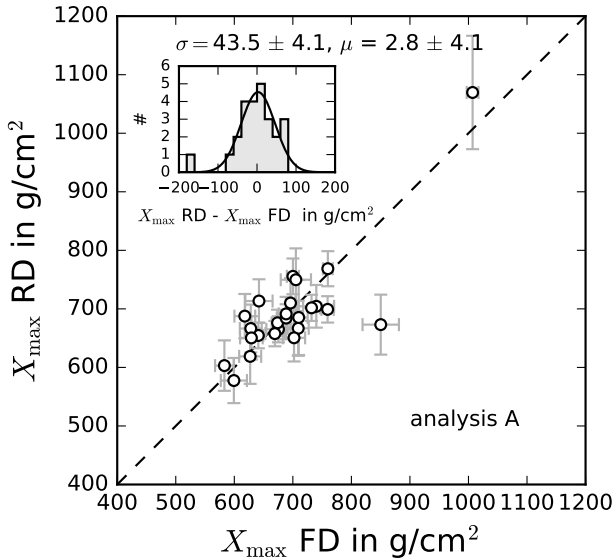
Figure 3. The depth of shower maximum X_{max} as determined with AERA correlates well with the X_{max} value determined from the Auger fluorescence detectors [11]. The combined FD-radio resolution is approximately 45 g/cm^2, and the radio-only resolution is of order 35-40 g/cm^2.

Figure 4. A simulation study of the separation power between proton- and iron-induced air showers shows that combined measurements of the radiation energy, $S_{\mathrm{RD}}^{\rho_\theta}$, and the muon content at a lateral distance of 600 meters, ρ_μ^{600}, provide very good mass composition sensitivity at all zenith angles [13]. In contrast, combined measurements of the electron number N_e and the muon content lose separation power towards higher zenith angles, as the electromagnetic cascade dies out before the shower reaches the ground. Detector effects are not included in this study.

ment with the values measured for the same showers with the fluorescence detectors [11], see Figure 3. The combined FD-radio resolution is approximately 45 g/cm^2, i.e. the radio-only resolution is of order 35-40 g/cm^2. This is likely limited by the sparsity of the radio array, as measurements with much denser radio arrays have yielded X_{max} resolutions below 20 g/cm^2 [12].

Another option for mass composition studies with radio antennas lies in their pure measurement of the energy in the electromagnetic component of an air shower. Combined with a measurement of the muon content of air showers, for example by the AMIGA underground muon detectors, this allows mass-composition studies through a completely different method. This approach has particular potential for inclined air showers, for which a classical measurement of the electron number at the ground is no longer feasible (the electromagnetic cascade dies out before reaching the ground due to the large atmospheric mass overburden). As radio signals are not significantly attenuated in the atmosphere, radio detection at these geometries allows the determination of the energy in the electromagnetic cascade, while particle detectors such as those of the SD will provide a clean measurement of the muonic cascade. The sensitivity for mass-composition measurements arising from this complementarity is illustrated in Figure 4.

5 Radio measurements of inclined air showers

The radio emission from extensive air showers is strongly forward-beamed. For showers with near-vertical incidence, for which the shower maximum is located at a few kilometers above sea level, the emission thus illuminates a
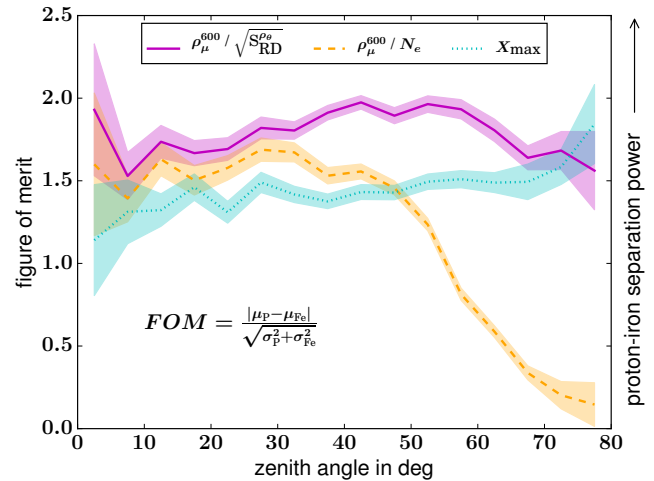
rather small area on the ground, of order hundreds of meters in diameter [14]. The area does not grow significantly with the energy of the primary particle because of the very steep lateral falloff of the radio signal and the even deeper depth of maximum for higher particle energies. As a consequence, radio detector arrays aiming to measure near-vertical air showers need a dense antenna spacing with a grid constant of at most a few hundred meters. Scaling such arrays significantly beyond the size of AERA is thus not cost-effective. For near-vertical showers, the energy reach is therefore limited to below 10^{19} eV, simply because the instrumentable area is limited.

In contrast, for inclined air showers, due to the vastly increased atmospheric mass overburden, the shower maximum is typically dozens of kilometers away from a ground-based antenna array. Consequently the emission is bound to be distributed over a much larger area [14]. This has recently been confirmed experimentally with AERA data [15] as presented in Figure 5: The distance of the radio detector station farthest from the air-shower axis which still measured a clear radio pulse increases significantly with the air-shower zenith angle. At the highest zenith angles, the lateral extent of the radio-emission footprint can exceed two kilometers in the shower plane. Projection to the ground then yields areas of more than 2 km $\times$ 2 km $\times$ sec(83°) $\times$ π = 103 km^2 illuminated with measurable radio signals. This allows radio detection of inclined air showers with very sparse radio arrays. In fact, we have demonstrated that a grid constant of 1.5 km, the same as that of the Auger SD, is sufficient for the detection of inclined air showers [15]. For inclined air showers, radio detection then provides a pure measurement of the electromagnetic component of the air shower,
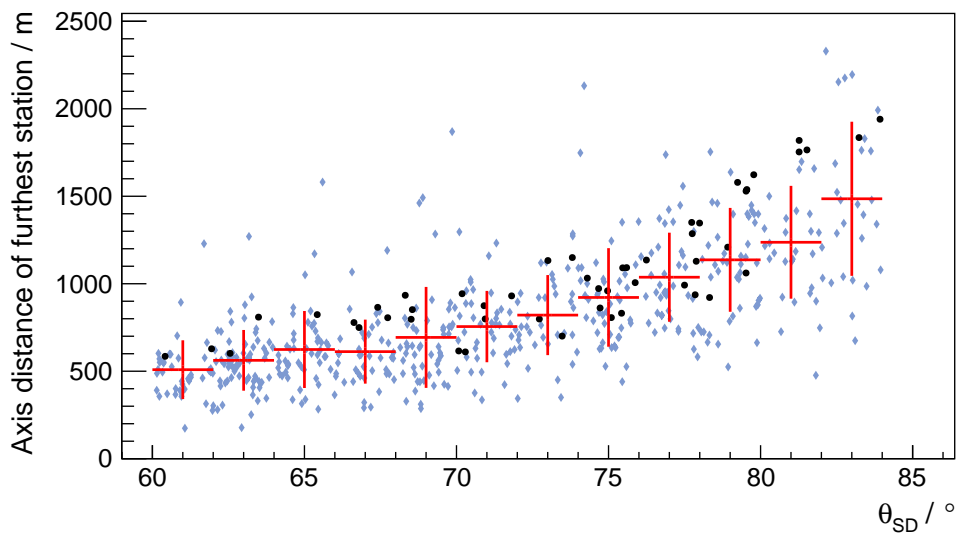
Figure 5. With increasing zenith angle, the farthest distance from the shower axis at which a detectable radio signal was measured by AERA grows significantly. At the highest zenith angles, detectable radio signals illuminate areas larger than 100 km^2.

while the SD measurements provide the pure muon content. As described above, this opens the possibility for mass-composition studies of inclined air showers.

Motivated by these findings, we will equip each water-Cherenkov detector of the SD with one radio antenna as part of the ongoing AugerPrime upgrade [16]. The details of this endeavor are described in a dedicated article [17].

6 Conclusions

The Auger Engineering Radio Array, an array of 150 autonomous radio detector stations covering a total area of 17 km^2, measures extensive air showers in the energy range of 10^{17} eV to several 10^{18} eV via their radio emission in the 30 to 80 MHz band. AERA explored many different approaches for the experimental design as well as several analysis strategies, and has made important contributions to leading the radio detection technique from pioneering prototypes to maturity.

In particular, we have demonstrated that the energy deposited in the form of radio waves on the ground, the *radiation energy*, can be measured accurately and is a reliable estimator for the energy in the electromagnetic cascade of an extensive air shower. This quantity has a well-defined physical meaning and can be measured and compared among radio detectors worldwide. As such, it is a very useful means to cross-calibrate the energy scale of different cosmic-ray experiments, and can even be used to validate the energy scale on the basis of first principle calculations.

Mass composition sensitivity is also present in radio signals. We have successfully reconstructed the depth of shower maximum of air showers from radio measurements with AERA, and they are in agreement with measurements from the Auger fluorescence detector. Another way to determine the mass of primary cosmic rays with the help of radio measurements lies in combining radio detection with

muon measurements, as are provided for near-vertical geometries by the Auger AMIGA detectors and for inclined air showers by the Auger surface detector.

Finally, we have established experimentally that inclined air showers illuminate areas of dozens or even more than a hundred km^2 with measurable radio signals. Hence, arrays with grid constants of a kilometer or larger can measure inclined air showers with reasonable antenna multiplicity. This allows radio measurements up to ultra-high energies, and yields very complementary information to that provided by the water-Cherenkov detectors of the SD. Consequently, as part of the AugerPrime upgrade, we will deploy a radio antenna on top of each water-Cherenkov detector to extend the composition-sensitive measurements of AugerPrime to inclined air showers. At the same time, we will continue to operate AERA, which is focused at energies around the EeV scale.

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