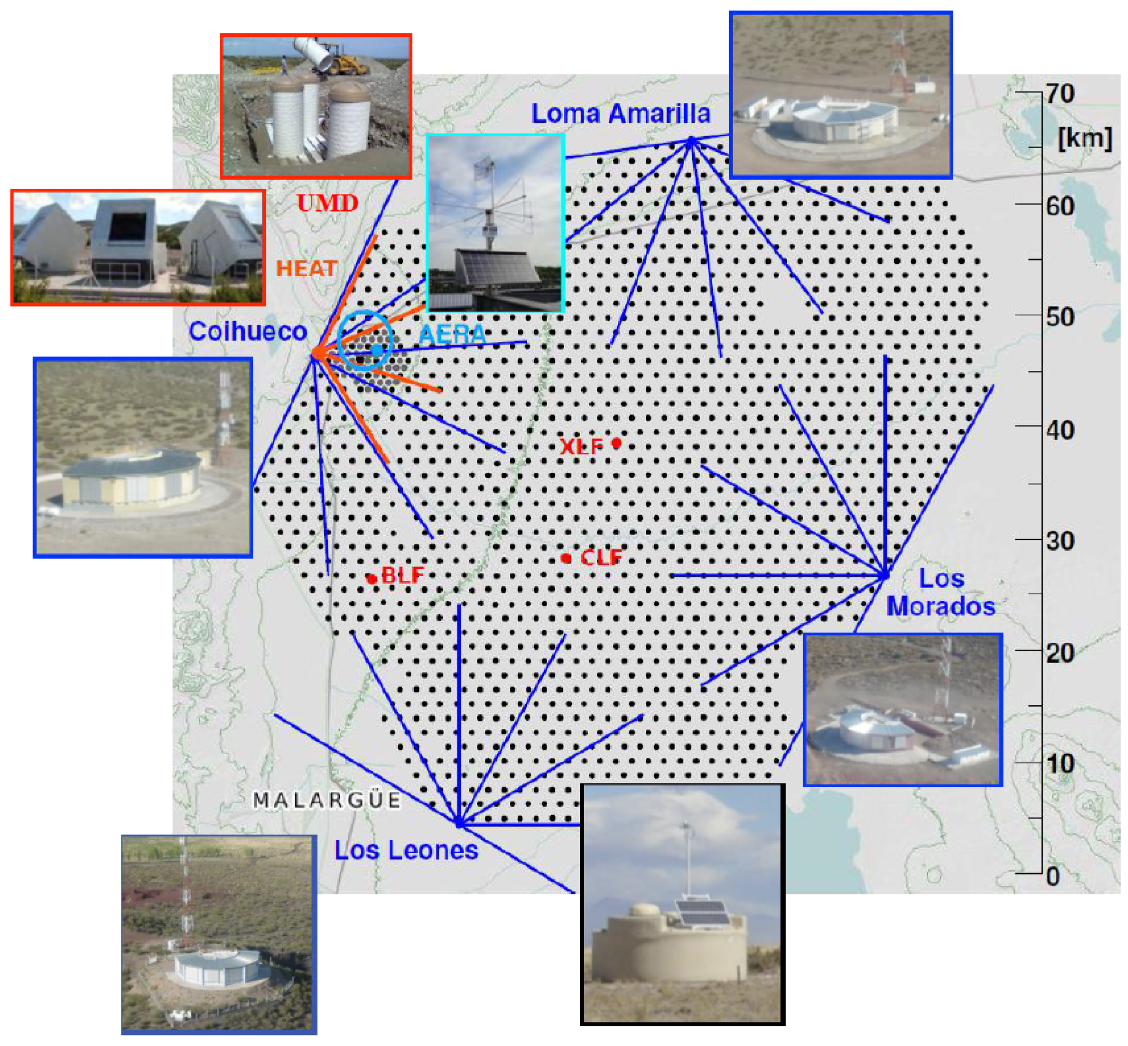
Radio detection of cosmic rays in the Pierre Auger Observatory

Abstract

Ultra-high-energy cosmic rays (UHECRs) are studied with giant ground-based detector systems – such as the Pierre Auger Observatory – recording extensive air showers, induced by cosmic ray particles in the atmosphere. Extensive air showers consist of charged particles that undergo acceleration in the atmosphere and thus they are a source of radio emission, which can be detected by radio antennas. In the last decade, a huge progress has been made in measuring the characteristics of air showers based on their radio signal and the technique of their radio detection has reached maturity. As part of the ongoing AugerPrime upgrade of the Pierre Auger Observatory, water-Cherenkov detectors will be equipped not only with scintillators, but also with radio antennas, creating the world's largest radio detector, covering an area of 3000 km². The new radio detector will operate together with the upgraded surface detector (water-Cherenkov and scintillator detectors), providing a unique setup to measure the properties of extensive air showers. We outline the basics of air showers radio detection, the concept and design of the AugerPrime Radio Detector.

The Pierre Auger Observatory and motivation for its upgrade



Water-Cherenkov stations
- SD1500 : 1600 stations, 1.5 km grid, 3000 km²
- SD750 : 61 stations, 0.75 km grid, 25 km²

4 Fluorescence Sites
- 24 telescopes, FoV 30 deg
- 3 high elevated telescopes (HEAT), FoV 30 deg

Underground Muon Detectors under construction
- 7 prototype stations

AERA radio antennas
- 153, 17 km²

+ Atmospheric monitoring devices

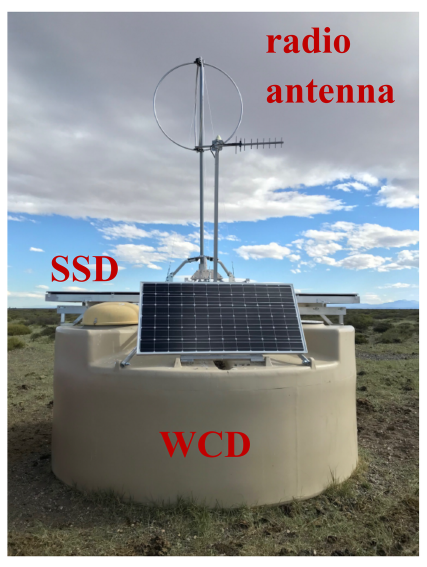
- Sources, acceleration mechanisms, and mass composition of ultra-high-energy cosmic rays (UHECRs) still remain mysteries.
- In addition, simulations of their interactions with the atmosphere show a significant muon deficit with respect to measurements.

To address these issues, the Pierre Auger Observatory (shown above) is currently undergoing a significant upgrade, called AugerPrime. The main goal of this upgrade is to improve the sensitivity of primary particle mass measurements by disentangling the electromagnetic and muonic components of air showers.

Design of the AugerPrime Radio Detector

For several years, the Auger Engineering Radio Array (AERA), an array of more than 150 radio detector stations covering an area of about 17 km², has been successfully recording air showers. To fully utilize detection capabilities of the radio technique, the existing radio detector will be extended to the entire Observatory.

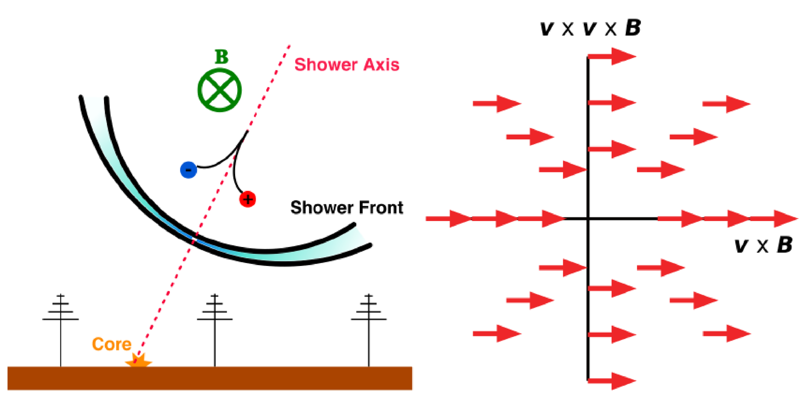
- It will provide complementary information on energy and mass of the cosmic ray primaries with respect to particle detectors.
- As part of AugerPrime, each water-Cherenkov detector (**WCD**) of the surface detector array (**SD**) will be supplemented both with a scintillator (**SSD**) and a radio detector (**RD**).



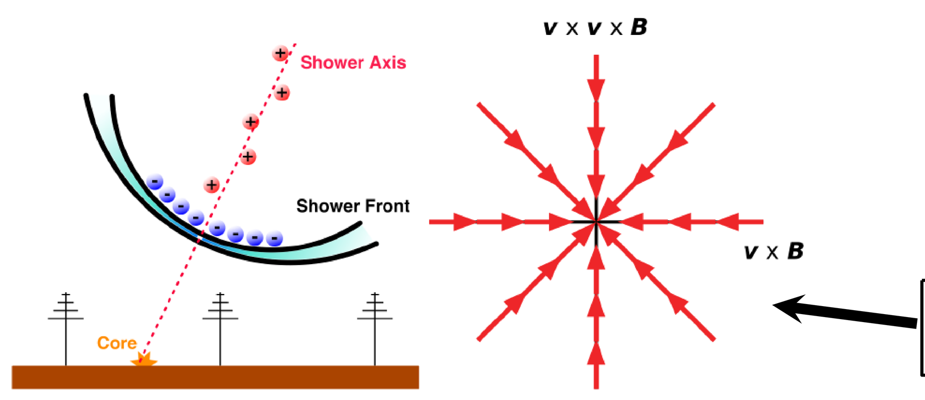
The AugerPrime radio array will consists of 1661 dual-polarized (orthogonally) short aperiodic loaded loop antennas (SALLAs). The antennas are fully integrated with the upgraded SD stations and will receive triggers from the water-Cherenkov detectors (WCDs).

SALLAs:
- provide a minimal design that fulfills the need for ultra-wide band sensitivity (30-80 MHz)
- robust and easy to manufacture
- low costs for production and maintenance in a large-scale radio detector.

Mechanisms of air shower radio emission



Geomagnetic effect (main contribution, linearly polarized): geomagnetic field deflects e⁻ and e⁺ in the opposite directions leading to transverse current varying over time

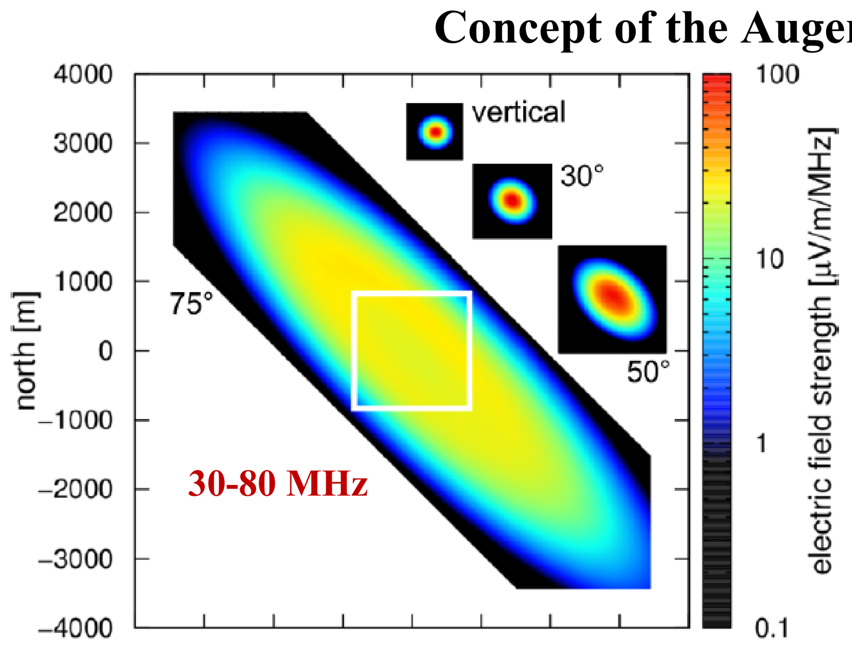


Askaryan effect (typical contribution ~10%, radially polarized): e⁺ annihilation with e- of air atoms leading to time variation of e⁻ excess in the shower front

polarization in the plane perpendicular to the shower axis

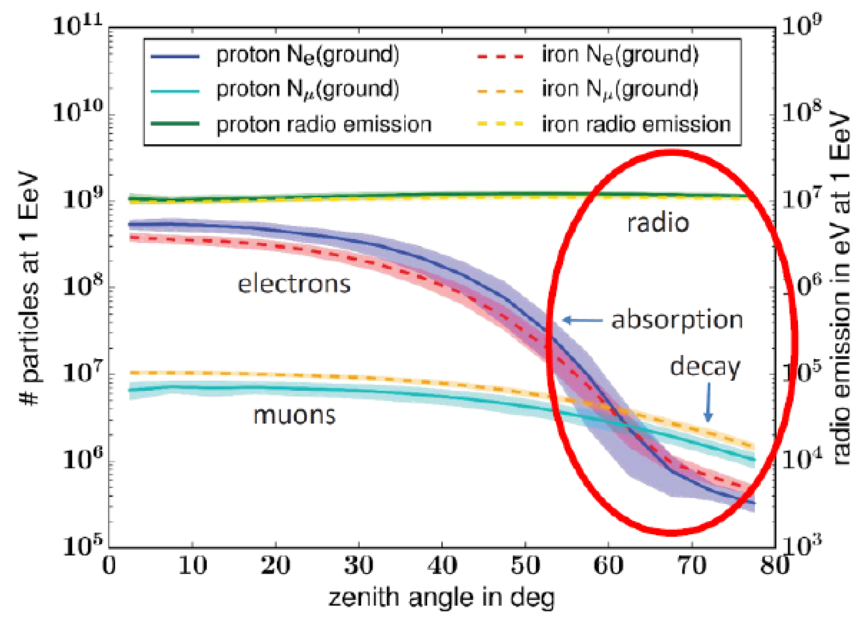
- Radio signal is a short pulse (~100 ns) emitted near the shower maximum. Signal compression in time (geometric effect) leads to its amplification in the forward direction.
- **Superposition of geomagnetic and Askaryan emission (different polarizations) leads to east-west asymmetry of the radio footprint on the ground.**

Concept of the AugerPrime Radio Detector



Footprint of the shower radio emission on the ground. The size of the footprint increases with the shower zenith angle.

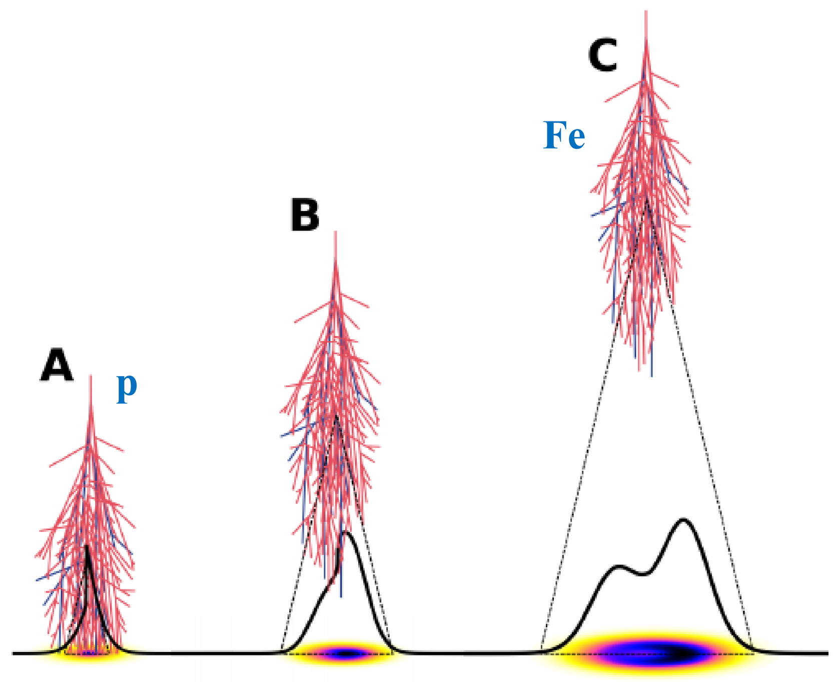
- Observations of air showers by a sparse antenna array with 1.5 km spacing (as is the case with the planned RD) is only feasible for inclined showers (zenith angles larger than ~60°), where the radio footprint is large enough to cover several radio antennas.



Number of e⁻ and ⁻ reaching the ground as a function of air shower zenith angle. For comparison, strength of the corresponding radio signal is also shown.

- The radio emission propagates without attenuation through the atmosphere.
- The electromagnetic cascade is mostly absorbed in the highly inclined showers.

- The RD delivers accurate measurements of the electromagnetic energy of air showers, while the WCD measures the virtually pure muon content of inclined air showers (due to absorption of electrons). **Thus, the detection of highly inclined air showers with the RD and WCD provides a very pure electron-muon separation, which offers a wealth of information, in particular about the mass of the primary cosmic ray.**
- **For "vertical" air showers (zenith angles below ~60°), the two shower components are disentangled by combining WCD and SSD measurements.**

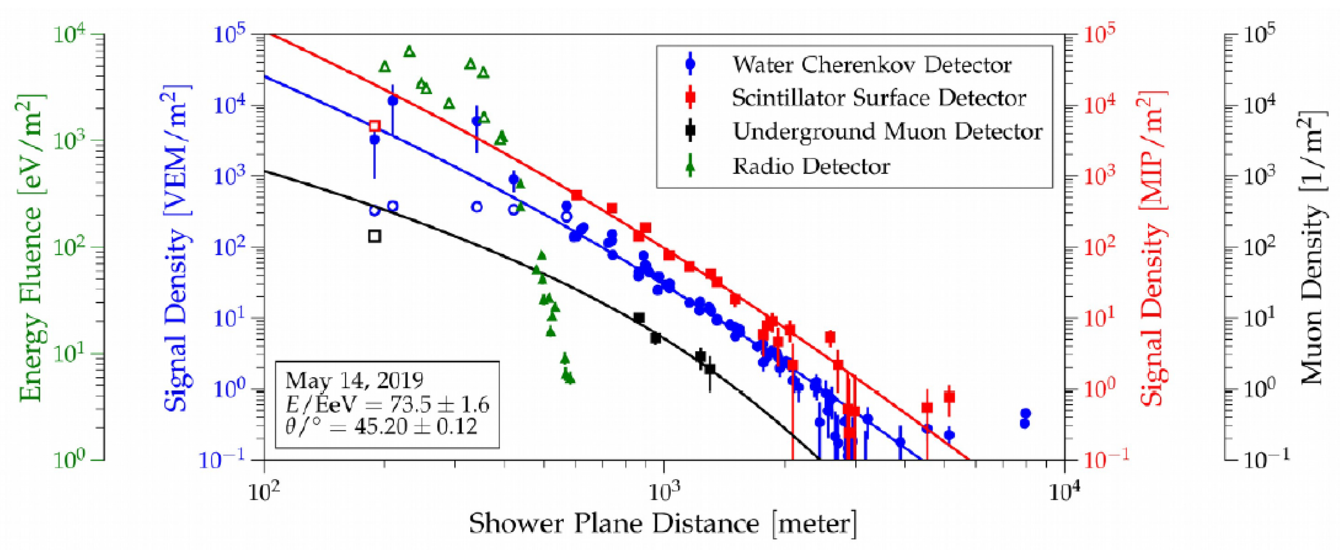


The radio footprint shape depends strongly on particle mass and can be used to probe the cosmic-ray mass composition:
- heavier primary nucleus interact higher up in the atmosphere and hence produce a wider footprint on the ground than
- lighter primary particle

The radio detector array provides:
- calorimetric energy measurements (integration of the radio signal on the ground)
- determination of the atmospheric depth of the shower maximum, i.e. X_{max}
- precise measurement of the shower geometry
- 100% duty cycle

Summary

- The AugerPrime Radio Detector will be the world's largest radio detector, covering 3000 km². It will operate as a part of the upgraded surface detector providing a unique multi-hybrid setup to measure the properties of extensive air showers up to the highest energies.



An example of a real multi-hybrid event, i.e. event observed simultaneously by all various detectors of the Pierre Auger Observatory. Shown are lateral distributions of air shower signal measured by WCD, SSD, UMD (underground muon detector), as well as by RD as a function of the distance to the shower core.

- The main objective of the radio upgrade is to measure highly inclined air showers, extending the sensitivity of the mass measurements (by providing pure electron-muon separation of the shower components) to zenith angles in the range between 65° and 85°, for which the scintillator upgrade is not effective (due to the geometry of SSD).
- The Auger Radio Detector is a natural next step towards future cosmic-ray experiments. It will allow to evaluate the detector technology, improve reconstruction methods, and study the physics performance of huge sparse radio arrays.

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