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AugerNext: R&D studies at the Pierre Auger Observatory for a next generation ground-based ultra-high energy cosmic-ray experiment

Andreas Haungs[*1] **for the Pierre Auger Collaboration**[2 †]

[1]*Karlsruhe Institute of Technology - KIT, Institut für Kernphysik, 76021 Karlsruhe, Germany*
[2]*Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina*
E-mail: auger_spokespersons@fnal.gov

The findings so far of the Pierre Auger Observatory and those of the Telescope Array define some requirements for a possible next generation global cosmic ray observatory: it needs to be considerably increased in size, it needs enhanced sensitivity to composition, and it has to cover the full sky. At the Pierre Auger Observatory, AugerNext aims to conduct some innovative initial research studies on a design of a sophisticated hybrid detector fulfilling these demands. Within a European supported ASPERA/APPEC (Astroparticle Physics European Consortium) project for the years 2011-2014, such R&D studies primarily focused on the following areas: i) consolidation of the detection of cosmic rays using MHz radio antennas; ii) proof-of-principle of cosmic ray microwave detection; iii) test of the large-scale application of new generation photo sensors; iv) generalization of data communication techniques; and v) development of new schemes for muon detection with surface arrays. The AugerNext Consortium consists of 14 principal investigators from 9 countries.[‡] This contribution summarizes some achievements of the R&D studies within the AugerNext project.

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[*]Speaker.

[†]Full author list: http://www.auger.org/archive/authors_2015_06.html

[‡]Andreas Haungs, KIT, Germany; Johannes Blümer, KIT, Germany; Martin Erdmann, RWTH Aachen, Germany; Karl-Heinz Kampert, University of Wuppertal, Germany; Ad M. van den Berg, KVI Groningen, The Netherlands; Zbigniew Szadkowski, University of Lodz, Poland; Henryk Wilczynski, Institute of Nuclear Physics PAN, Cracow, Poland; Antoine Letessier-Selvon, IN2P3/CNRS, France; Mario Pimenta, LIP - Laboratory of Instrumentation and Experimental Particles Physics, Portugal; Enrique Zas, University of Santiago de Compostela - USC, Spain; Valerio Verzi, INFN Roma Tor Vergata, Italy; Iliana Brancus, IFIN-HH Bucharest, Romania; Masahiro Teshima, MPI für Physik, München, Germany; Martina Bohacova, Institute of Physics - FZU, Prague, Czech Republic.

1. Introduction

The Pierre Auger Observatory [1] in Argentina is the largest cosmic-ray experiment in the world and in operation since 2004. Results from this observatory have shown that the spectrum of cosmic rays exhibits a suppression at about 50 EeV [2, 3]; that events with an energy larger than 50 EeV show largest departure from anisotropy [4, 5]; and that data are consistent with a gradual increase of the average mass of cosmic rays for energies above 59 EeV, at least [6]. Presently, the Observatory is initiating a program of upgrades to achieve a better mass sensitivity at the highest energies [7]. At the same time, the Telescope Array Collaboration, with an experiment located in the Northern Hemisphere, has also seen the suppression, but the composition inferred is interpreted as being in agreement with light mass primaries, and a large hotspot in the distribution of the arrival direction of the highest energy cosmic rays has been observed [8, 9, 10]. In coming years the Telescope Array will be enlarged in area by a factor of four to study this hotspot with better statistics.

The findings of these two experiments define already some requirements for a next generation experiment: (i) To acquire sufficient statistics for the highest energies, a sensitive area of several tens of thousands of square kilometers is necessary. (ii) If it is true that a mixed composition around the suppression energy exists, an improved sensitivity to the elemental composition is required. (iii) Due to substantial structural differences with direction in the mass distribution of the nearby Universe, the full sky needs to be investigated with equally high quality. A comprehensive R&D study is needed to fulfill these requirements for the design of such a next generation cosmic-ray experiment.

First ideas are evaluated within the global cosmic-ray community towards such an observatory, i.e., GCOS, the "Global COSmic-ray observatory", is in discussion, where approximately $90,000\text{km}^2$ shall be instrumented. GCOS will be organized in several arrays in a few countries of the Southern and Northern Hemisphere, respectively. These arrays need autonomous detectors with sophisticated features and monitoring modes to operate for ca. 30 years in a maintenance-free way. GCOS will have synergies with the high-energy neutrino detectors IceCube, KM3NeT and the gamma observatory CTA for complementary measurements needed to perform multi-messenger particle astronomy. A realization of GCOS at some time within the next decade needs efforts to commence immediately, including the development of new detection technologies. The AugerNext project as well as the intermediate step of upgrades of the Pierre Auger Observatory and of the Telescope Array experiment are preparatory work in this direction. AugerNext contributes to this process with the aim of performing innovative research studies, primarily at the Pierre Auger Observatory, in order to prepare a proposal fulfilling the aforementioned demands.

AugerNext is a project which was supported by 9 European funding agencies for three years from the end of 2011 to the end of 2014. The AStroParticle ERAnet (ASPERA) was a network of national European government agencies responsible for Astroparticle Physics [11] funded by the European Community. One element of ASPERA was to organize targeted R&D and design studies in view of the realization of future astroparticle infrastructures identified in the ASPERA/APPEC[1] Roadmap (available at [11]), where the proposals should demonstrate a clear added value to the applicants' partnership over and above what could be achieved individually. Within the Pierre Auger

[1] APPEC is the interest group of the Astroparticle Physics European Consortium [12].

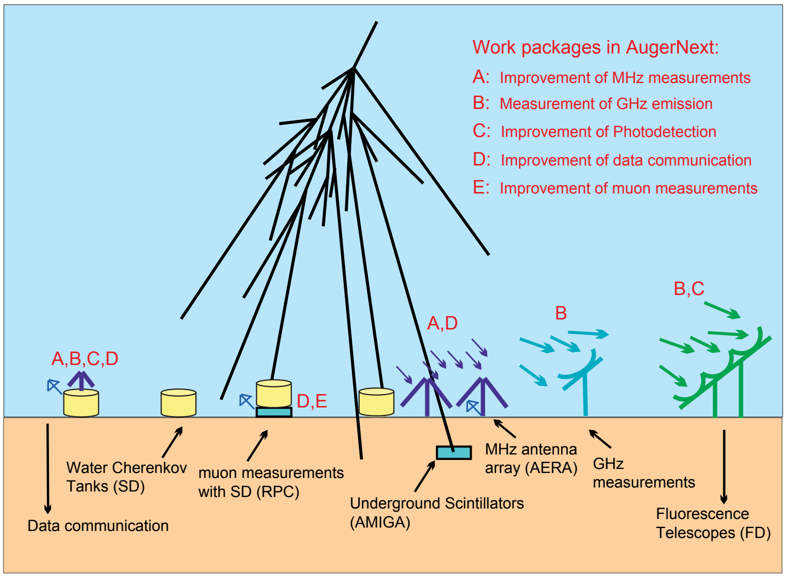

Figure 1: Schematic view of the detection of extensive air showers with a Pierre Auger Observatory-like experiment and the connection of the work packages proposed in the AugerNext project.

Collaboration a consortium was formed to propose studies for a next-generation cosmic-ray experiment and the utilization of new innovative detection methods. AugerNext aims to significantly strengthen R&D efforts in specific areas. Fig.1 sketches the topics explored in the context of the existing Pierre Auger Observatory located in Argentina. These topics were chosen by available expertise of the consortium partners and are defined as work packages where specific five-year goals have been formulated, all of a highly innovative character. The work will be continued by support on an institutional level as best as possible.

2. The work packages and results so far

(A) Investigation of MHz radio emission in air showers The general goal for the 5 year project was to establish the detection method as a hybrid or even standalone technique, and in particular to estimate the resolution and sensitivities of the technique to energy, mass, and arrival direction of the cosmic ray. The hope is that radio can replace the fluorescence detection technique with similar reconstruction quality on primary parameters, but with significantly higher duty cycle. Within the AugerNext project specific topics have been worked on:

1. A hybrid demonstrator was set up (i.e., surface detector including integrated radio antenna) for common trigger and combined analysis of the complementary information at individual surface detectors. This approach named EASIER [13] could reveal lateral distributions of the radio signal with a very large distance between the antennas and could give the proof-of-concept for the particle-radio hybrid technique.
2. The Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory has been set up in order to investigate the radio signal from air showers in detail [16]. The radio emission gives information complementary to particle detectors as the pure electromagnetic

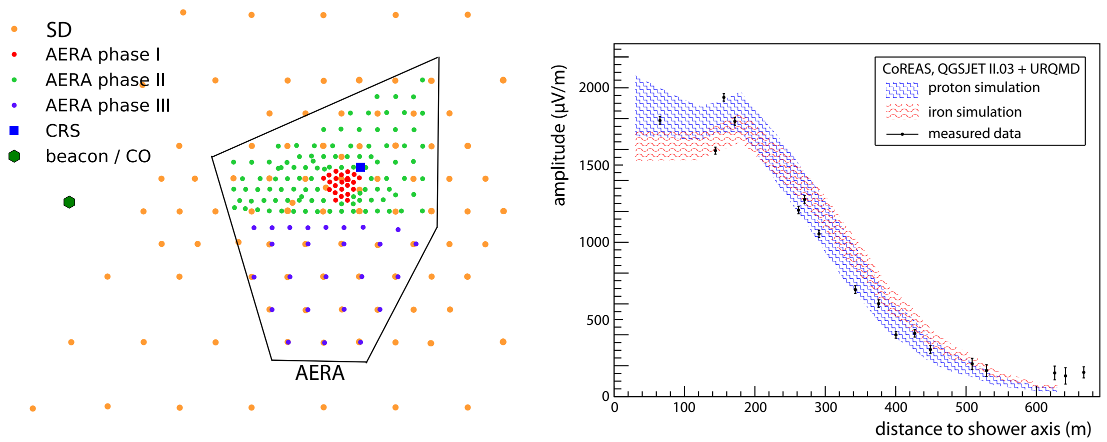

Figure 2: Map of the Auger Engineering Radio Arrays. AERA consists of 153 antenna stations and covers an area of 17 km^2 (left panel). Right: lateral distribution of the radio signal of one of the high-energy events measured by AERA in comparisons with detailed simulations for proton or iron primaries (CoREAS [14] in this case, but ZHAires [15] leads to similar results). This shows that even complicated emission patterns are understood and reproduced by the sophisticated simulations.

component is selected. Self-trigger has been proven, but is difficult due to radio frequency interference (RFI) faking the radio shower signal. The hardware used in AERA (Fig. 2) was and is still being optimized for large-scale applications, where further cost reduction is an important issue. Radio detectors can be built in a cost effective way, but this depends on two main aspects, the cost of an individual radio detector station and the needed density of these sensors. A caveat of the radio technique lies in the relatively small footprint of the detectable signal for vertically arriving air showers. However, the footprint increases drastically when more inclined events are measured.

3. The AERA array was extended to be sensitive also to horizontally arriving air showers. With radio the electromagnetic component can still be measured for those showers, where particle detectors see the muon component only.

The data of AERA and other radio experiments in combination with sophisticated simulation tools have led to a deep understanding of the radio emission in air showers [17]. Recent data analyses [18] have shown that, with the radio signal, a very good angular resolution as well as an energy resolution of better than 20% can be reached. In addition, the lateral distribution and the form of the wavefront of the radio signal are sensitive to the longitudinal shower development. This allows the determination of the position of the shower maximum and, therefore, a reconstruction of the elemental composition. AERA, covering the largest area and highest energies in radio hybrid experiments can investigate the emission mechanisms via detailed polarization measurements. Two radio emission mechanisms, the geomagnetic and the Askaryan effects, contribute mainly to the radio signal from air showers. For individual showers AERA can determine the contribution of the Askaryan mechanism to the total signal to 14% [19] on average for the measured events.

(B) Detection of the microwave emission in air showers P. W. Gorham et al. [20] proposed in 2008 the possible observation of extensive air showers in the microwave band. This idea was motivated by the observation of a signal in the 1.5-6 GHz band during the passage of an electron beam in an anechoic chamber. This recorded signal was interpreted as molecular Bremsstrahlung radiation (MBR), i.e., an emission produced by low-energy electrons scattering on the atmospheric molecules. Radio emission produced by this mechanism presents interesting features: it is expected to be isotropic and unpolarized, with a very low natural background. If true, its main advantage is the possibility of instrumenting a large area with 100% duty cycle with a negligibly small atmospheric attenuation, using relatively cheap equipment.

One defined five-year goal in AugerNext concerned the question of whether this technique provides the possibility of measuring the primary parameters of high-energy cosmic rays.

1. A hybrid demonstrator called EASIER was set up (i.e., Auger tanks including integrated horn antennas). A few events have been detected [21], and a detailed analysis has been performed of a possible contribution to the measured signals by the molecular bremsstrahlung effect.
2. A non-imaging detection system, called CROME, was externally triggered by the KASCADE-Grande detector. The CROME setup was well-suited for the detection of pulses of a few nanoseconds duration as expected for cosmic-ray showers. For more than 30 air-shower events a signal in the Gigahertz range could be identified in coincidence with KASCADE-Grande. The cores of these showers are distributed in a ring around the detectors, hinting to an emission which is boosted in the forward direction (Fig. 3). Applying simulations developed for the MHz frequency range was able to confirm the pattern and the polarization of the measured radiation. An isotropic, unpolarized component of the signal (which would hint to the predicted molecular Bremsstrahlung radiation) is still not excluded, but definitely smaller than expected by Gorham et al. in 2008. Therefore, the measurement of the Gigahertz emission in air showers seems not to give a reasonable alternative to the fluorescence measurement for large-scale cosmic-ray experiments [22]. The setup measuring simultaneously in the L-band could not detect a shower signal, mainly due to the increased noise background in this frequency band [23].
3. The feasibility of detecting extensive air showers (EAS) by a radar technique has been investigated. It is based on the observation of the radio waves scattered off the short-lived plasma produced in the atmosphere by the high-energy particles of the shower. Simulations show that the signal received by the detector is strongly dependent on the geometry of the detection system. Moreover, the strength of the received signal depends on the frequency of the emitted radar wave. The crucial point is to choose the optimum combination of the radar system parameters. Based on the first results, however, no high sensitivity will be reached by any reasonable equipment [24].
4. The aim of FDWave is to develop a microwave telescope equipped with a matrix of radio receivers looking to a different part of the sky. The idea is to install GHz sensors in two fluorescence telescopes (FD) of the Auger Observatory. The optimal antenna that could be placed in the FD camera is a Low Noise Block working in the Ku band (11 GHz). A detailed simulation of the detector equipped with this radio sensors shows that a good effective aperture of the telescope can be attained. Of course the feasibility of this new detection technique depends on the emission intensity and the degree of coherence of the underlying process. The latter has been studied by the AMY experiment using the 510 MeV electron

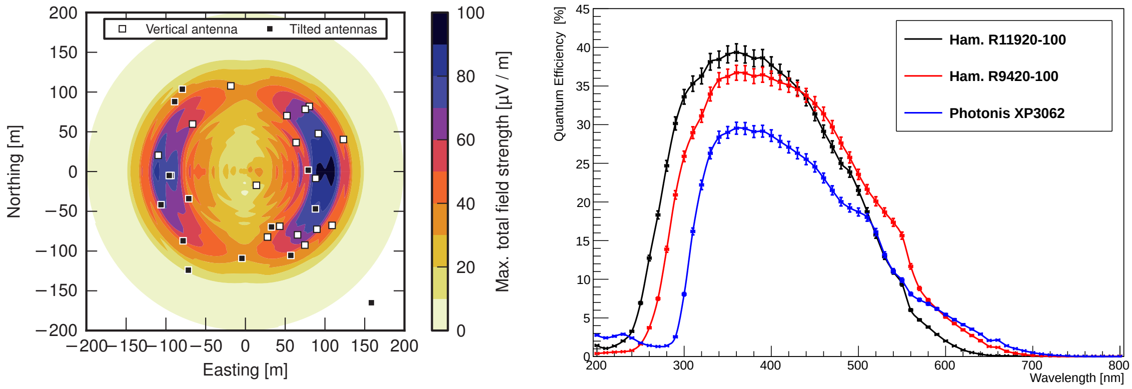

Figure 3: Left: Distribution of the cores of the detected events by CROME relative to antenna positions. The underlying color distribution is the footprint of the C-band (3.4-4.0 GHz) of an iron-induced cosmic-ray shower predicted by a CoREAS simulation [22]. Right: Quantum efficiencies measured in the laboratory as a function of wavelength for different types of photomultiplier tubes [26].

beam at the Beam Test Facility of Frascati INFN National Laboratories. The MBR has been studied in a wide frequency range, between 1 and 20 GHz, within a huge (2 m x 2 m x 4 m) anechoic Faraday chamber. Contrary to what has been reported in [20], the signal has been found very prompt in time like the Cherenkov radiation and it has been demonstrated that the observed coherence is caused by the particular time structure of the LINAC beam [25]. A preliminary analysis of the AMY data shows that the intensity of the observed signal is significantly less than the one reported in [20].

(C) Improvement of photo sensors There are structured activities worldwide to improve photo detectors. These concern vacuum photomultiplier tubes as well as the development of silicon photomultipliers (SiPM). One objective in this overall package is the development of a new generation of focal planes for cosmic-ray air-fluorescence and Cherenkov imaging, achieving better light detection efficiency and a better spatial and angular resolution. Therefore, within AugerNext we want to test the latest developments, in order to study their capability for a next-generation experiment.

1. After many years of not very significant advances in quality parameters of vacuum photomultiplier tubes, important progress has been made very recently with photo cathodes becoming available with improved quantum efficiencies. Super-bialkali (SBA) photo cathodes reach quantum efficiencies (QE) of about 35%, while ultra-bialkali (UBA) ones reach QEs of even up to 43% (Fig. 3, right panel). The aim is to gain experience with devices in real environments and to cooperate with manufacturers for improving their overall characteristics. High quantum efficiency PMTs are tested at the Pierre Auger Observatory in both fluorescence telescopes and surface detectors [26].
2. A SiPM focal-plane element for the FD (FAMOUS, see Fig. 4) was designed, and a first prototype built and tested, as a prototype fluorescence telescope with a special light collecting optical system of Winston cones to increase the sensitive area [27]. The experience in

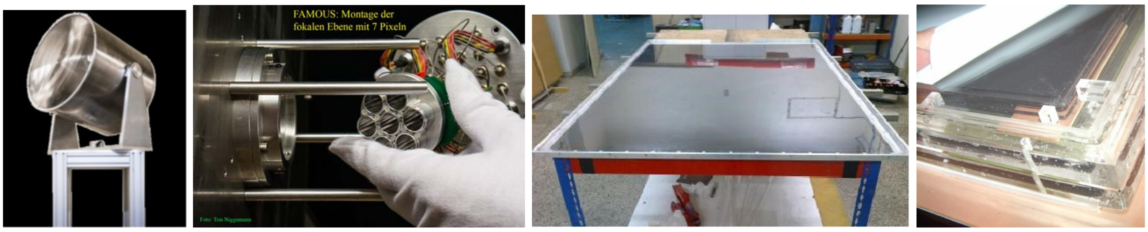

Figure 4: From left to right: photo of the compact FAMOUS prototype camera with the Fresnel lense and of the installation of a 7-pixel camera to FAMOUS, the overall photo of the RPC engineering prototype and a detail of the RPC structure.

photodetection with SiPMs is also the basis of tests aiming at the potential implementation of those devices as a new readout system for the upgraded detectors.

(D) Generalization of the data communication system A crucial aspect in large arrays is the data transfer. An advanced technique has to be developed or adapted from commercial applications (e.g., mobile phone technique). Autonomous detector stations in large-scale air-shower arrays will be part of a distributed sensor network connecting all local stations to a central data-storage unit. Within the project we have developed new strategies for data communication systems with flexible application possibilities for large-scale remote-detector arrays. We compared different approaches in both custom-made in-house or commercially-provided systems to reach a general, worldwide applicable remote-controlled communication system. In particular:

1. One investigation focused on the adoption of a commercial, self-healing communication systems implemented in AERA. We procured a commercial system of 160 radio-communication antennas. They have been installed and tested for their performance with respect to data rates and systems reliability. A high-bandwidth 802.11n commercial wireless system in the 5.8 GHz frequency band from Ubiquiti is used [28]. The system has shown within AERA that it provides a stable operation and with some additional investment can easily be scaled to larger applications.
2. Detailed simulation studies are performed to develop suitable network topologies. Due to the structure of the communications network which interconnects the detectors of a large observatory, a mesh topology has been considered and a gossip-type communication protocol has been analyzed. The performances are analyzed and compared with the ones obtained from the measurements.
3. A new, custom-made communication system in the 2 GHz range was developed which can transfer data over distances of 3 to 6 km with low power consumption. A long-term test was performed to investigate the stability, availability, failure rates, external pollution signals, etc, as well as to optimize the required signal strength at the sender and the receiver. The system was working, but was ultimately abandoned due to the success of the cheaper commercial system.

(E) Studies for a hybrid muon detector The objective in this work package is to show that muon detectors based on the Resistive Plate Chamber (RPC) technique (see Fig. 4) can operate under field conditions, i.e., demanding a low energy budget, low cost per unit area, and mechanical toughness. In particular, we want to explore the capabilities to measure new shower observables, or to improve the resolution of actual observables, namely sensitivity to the details of the hadronic cascade through muons. RPCs are fast and have a very good time resolution which could nicely be used to reconstruct single particle tracks and the longitudinal evolution of muons in a shower. In a hybrid operation with SD tanks this can considerably improve the composition sensitivity of a future detector. Within AugerNext we produced and tested with a first prototype the capability and robustness of RPC-based detectors for large-scale applications. We showed that RPCs can serve as a large, cheap, and robust timing detector. A first prototype (including readout electronics) is deployed in Argentina, where the data is presently being analyzed [29].

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