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AugerNext: innovative research studies for the next generation ground-based ultra-high energy cosmic ray experiment

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Abstract. The findings so far of the Pierre Auger Observatory and also of the Telescope Array define the requirements for a possible next generation experiment: it needs to be considerably increased in size, it needs a better sensitivity to composition, and it should cover the full sky. AugerNext aims to perform innovative research studies in order to prepare a proposal fulfilling these demands. Such R&D studies are primarily focused in 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 a new generation photo-sensors;
iv) generalization of data communication techniques;
v) development of new ways of muon detection with surface arrays.
These AugerNext studies on new innovative detection methods for a next generation cosmic-ray experiment are performed at the Pierre Auger Observatory. The AugerNext consortium consists presently of fourteen partner institutions from nine European countries supported by a network of European funding agencies and it is a principal element of the ASPERA/ApPEC strategic roadmaps.

1. AUGERNEXT

The Pierre Auger Observatory [1] is, worldwide, the largest cosmic-ray experiment and has operated in the Southern Hemisphere since 2004. Results from the 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 some anisotropy [4, 5]; and that data are consistent with a gradual increase of the average mass of cosmic rays with energy up to 59 EeV, at least [6]. On the other hand, the Telescope Array experiment located at the Northern Hemisphere has also seen the suppression, but no anisotropy has been observed, and the composition is in agreement with light mass primaries only [7]. The findings of these two experiments define requirements for a possible next generation experiment. To acquire, in a reasonable time, sufficient statistics for the highest energies above 50 EeV, an array of area of several ten-thousands of square kilometers is necessary. If the hints of the Pierre Auger Observatory prove true, that a mixed composition around the suppression energy exists, an improved sensitivity to the elemental composition is required. In addition, due to substantial structural differences with direction in the mass distribution of the nearby Universe, the full sky should be investigated with equally high quality. A facility fullfiling

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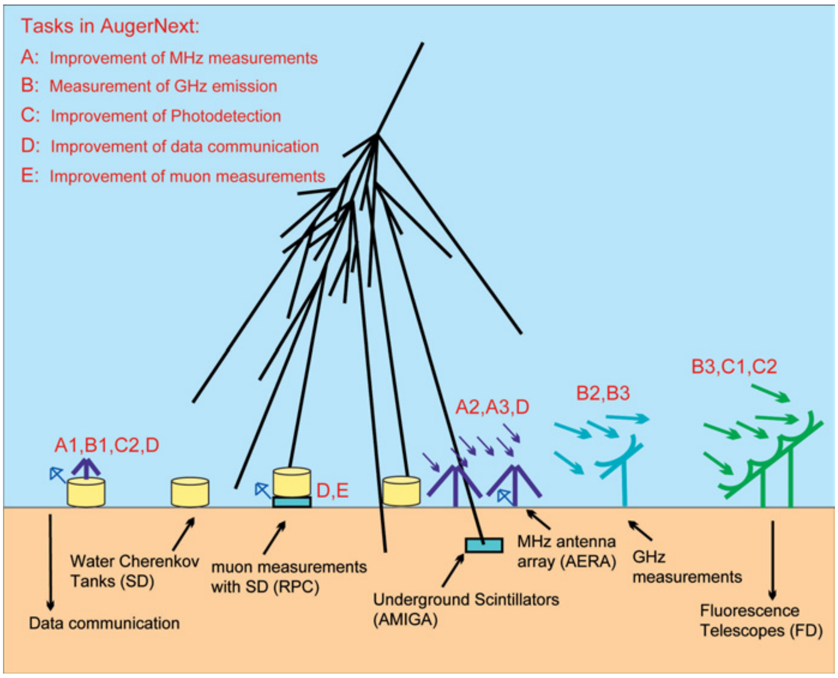

Figure 1. Schematic view of the detection of extensive air showers with a Pierre Auger Observatory-like experiment and the connection of the work packages proposed in the AugerNext project.

these requirements should be specified within the next years, with the intermediate step of upgrades of the Pierre Auger Observatory [8] and of the Telescope Array experiment [9], as well as exploratory studies of the capabilities of space observations of extensive air showers [10]. These specifications must include a thorough study of the scientific questions such an array should answer, as well as the formation of a world-wide group of scientists interested to follow these ideas (for which the present symposium provided a cornerstone).

AugerNext contributes to the process with the aim of performing innovative research studies, primarily at the Pierre Auger Observatory, in order to prepare a proposal fulfilling the above mentioned demands. R&D studies are focused on the following topics: consolidation of the detection of cosmic rays using MHz radio antennas, proof-of-principle of cosmic-ray detection at GHz frequencies, tests of the large-scale applicability of a new generation photo sensors, generalization of data communication techniques, and development of a new technique of muon detection with surface arrays. Figure 1 sketches these specific topics in the context of the existing Pierre Auger Observatory located in Argentina.

AugerNext is supported by 9 European funding agencies for three years, where the start of the project varies in the different countries from October 2011 to mid of 2012.

2. THE WORK PACKAGES AND FIRST RESULTS

The current project aims to significantly strengthen R&D efforts in specific areas. These areas were chosen by available expertise of the European partners involved and byprospects in structuring these efforts on a world-wide level. These areas are defined as work packages where specific 5-year-goals have been formulated, depending on the current level of investigations. Subtasks were selected which are appropriate for support from the involved funding agencies, i.e. having a highly innovative character.

2.1 (A) Investigation of MHz radio emission in air showers

For the radio-detection technique in the MHz frequency band many efforts have already begun. In particular at the Pierre Auger Observatory, an engineering array (AERA) is being set-up in order to investigate the radio signal in detail [11]. In principle this could replace the fluorescence detection technique. Recent data analyses [12] have shown that, with the radio signal, a very good angular resolution well below 1° as well as an energy resolution of around 20% can be reached. In addition, the lateral distribution of the radio signal is sensitive to the longitudinal shower development. This allows the determination of the position of the shower maximum and, by that, a reconstruction of the elemental composition is possible. Open questions are still the resolution in the determination of the shower maximum, and the self-trigger capability of the detection technique. Information about the shape of the lateral distribution has to be used to determine the required grid size of a future radio array and has to be optimized taking into consideration a realistic cost estimation. The concept of an integrated particle and radio detector seems to be promising, where its development has to be accompanied by detailed R&D studies.

The general goal for the next 5 years is to establish the detection method as a hybrid technique, in particular to estimate the resolution and sensitivities of the technique to energy, mass, and arrival direction of the cosmic ray.

Within the AugerNext project specific topics have been identified which are needed to advance this detection technique:

1. A hybrid demonstrator will be set-up (i.e. surface detector including integrated radio antenna) for common trigger and combined analysis of the complementary information at individual surface detectors. We follow this approach with EASIER [13].
2. The hardware presently used in the Auger Engineering Radio Array (AERA) [14, 15] has to be optimized for a large-scale application of the order of 300 km^2 which, with its 24 hours-per-day duty cycle cooresponds to the exposure of the fluorescence detector system of the Pierre Auger Observatory [16].
3. The standard AERA radio stations will be optimized to be sensitive also to horizontally arriving air showers, i.e. possibly neutrino-induced showers.

2.2 (B) Detection of the microwave emission in air showers

Recently, hope has risen that, also in the GHz frequency range, detection of high-energy air showers may be possible. As laboratory measurements [17] have indicated, the signal could originate from molecular bremsstrahlung emission processes in the atmosphere. Triggered by this, a number of initiatives were begun to prove the technique for the detection of ultra-high-energy cosmic rays. 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. At the Pierre Auger Observatory three different set-ups are in operation [18]: MIDAS and AMBER are prototypes of imaging parabolic dish detectors, while EASIER instruments surface detector tanks with a radio receiver of wide angular coverage. Complementary, the CROME experiment [19] is a setup where GHz radiation is measured with several parabolic antennas, each equipped with a multiple-receiver camera operating in the bands 3.4–4.2 GHz and 0.95–1.75 GHz. CROME operates in coincidence with the cosmic ray experiment KASCADE-Grande in Karlsruhe, Germany [20].

The general goal is now to answer the question of whether this technique provides the possibility of measuring the primary parameters of high-energy cosmic rays.

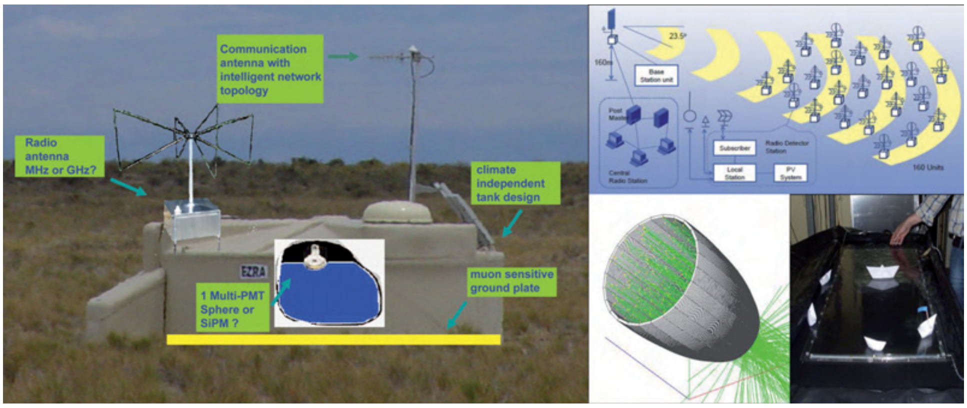

Figure 2. Schematic view of a possible future surface detector suitable for a next generation cosmic ray air-shower array (left panel). Beside this, a ray-tracing simulation of a Winston-Cone developed and under test for FAMOUS is shown. The lower right figure shows tests of the water tightness of a large Resistive Plate Chamber under operation. The right upper panel outlines a possible topology of a data communication system for the Auger Engineering Radio Array.

Within AugerNext, specific topics were identified to initiate such studies and they structure the efforts in the field:

1. A hybrid demonstrator has been set-up (i.e. SD tanks including integrated horn antennas) called EASIER. A first event has been detected already [18].
2. A non-imaging detection system, called CROME, has been set-up, externally triggered by the KASCADE-Grande detector. Within these investigations, a system for the absolute calibration of such devices will be developed. The CROME setup is well-suited for the detection of pulses of a few nanoseconds duration as expected from cosmic-ray showers. The first detected air-shower events now provide the basis for studies of the possible emission mechanism.
3. A test GHz-focal plane (FDWave) will be installed at a fluorescence telescope at the Pierre Auger Observatory [21].

2.3 (C) Improvement of photo sensors

There are worldwide structured activities to improve photo detectors. These concern vacuum photomultiplier tubes as well as the development of silicon photomultiplier (SiPM). The objective 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. Due to the future application of this new generation of focal planes for experiments such as AugerNext or upgrades of existing observatories, architectures that include principles such as high reliability, easy field maintenance with the lowest down-time achievable, and minimization of the total power budget are considered to be highly desirable. On the other hand, observations of high-energy cosmic rays by air-shower detection presently still rely solely on the application of vacuum photomultiplier tubes (PMT). After many years of no significant advances in quality parameters, important progress has been made very recently with photo-cathodes becoming available with improved quantum efficiencies. Super-bialkali (SBA) photo-cathodes reach quantum efficiencies (QEs) of about 35%, while ultrabialkali (UBA) ones reach QEs of even up to 43%. The aim is to gain experience with devices in real environments and to co-operate with manufacturers for improving their overall characteristics.

Therefore, within AugerNext we want to test the latest developments of the detectors with the Pierre Auger Observatory, in order to study their capability for a next generation experiment.

1. A SiPM focal-plane element for the FD (FAMOUS) will be designed, built, and tested. FAMOUS is a prototype fluorescence telescope using SiPMs and it has a special light collecting optical system of Winston cones to increase the sensitive area [22].
2. High quantum efficiency PMTs will be tested at the Pierre Auger Observatory in both fluorescence telescopes and surface detectors.

2.4 (D) Generalization of the data communication system

A crucial aspect in large arrays is the data transfer. Here, an advanced technique has to be developed or adapted from commercial applications (e.g., mobile phone technique) for AugerNext or other experimental efforts. Autonomous detector stations in large scale air-shower arrays (particle detectors or radio sensors) will be part of a distributed sensor network connecting all local stations to a central data storage unit. After in-station data analysis and processing, when parts of the dataset will be stored temporarily into local buffers, the information from each station will be retrieved in two successive steps. In the first step, the station will broadcast a message that it has registered an event at a well-defined (GPS) time. Time stamps from multiple stations will be analyzed in a sensor network. Such networks are characterized by specific network-embedded algorithms. These algorithms use the space and time information of these time stamps to decide if a possible air shower has been detected with at least three stations. After a positive decision, the network will send a query to the relevant stations to broadcast the additional data stored in their buffers. Subsequently, these data will be transported through the network for further analysis and data storage. Within the project we want to develop new strategies for data communication systems with flexible application possibilities for large-scale remote detector arrays. We will compare different approaches presently under investigation in both custom-made in-house or commercially provided systems to reach a general, worldwide applicable remote-controlled communication system. In particular:

1. The investigations will focus on the adaption of various commercial, self-healing communication systems.
2. Detailed simulation studies are performed to develop suitable network topologies.
3. A procedure will be worked out on how to compare different approaches, and this will be applied to the systems under investigations.

2.5 (E) Studies for a hybrid muon detector

Our objective is to show that muon detectors 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 Resistive Plate Chambers (RPCs) 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 reconstruct the longitudinal evolution of muons in a shower. They could also separate electrons from 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 will test the capability and robustness of RPC-based detectors for large-scale applications. Important milestones are:

1. Demonstration that RPC can serve as a large, cheap, and robust timing detector.
2. Development of a first prototype detector.

3. ORGANIZATIONALS

The AStroParticle ERAnet (ASPERA) is a network of national European government agencies responsible for Astroparticle Physics [23]. One instrument of ASPERA is to organize targeted R&D and design studies in view of the realization of future Astroparticle infrastructures identified in the ASPERA Roadmap (available at [23]). The second ASPERA Common Call for proposals has been launched on September, 15, 2010. This call was targeted towards future high-energy cosmic ray and neutrino mass experiments, where the proposals should demonstrate a clear added value to the applicants partnership over and above what could be achieved individually. Examples of possible R&D topics for this call are described in the ASPERA document *R&D for Astroparticle Physics* provided at the ASPERA website [23]. The call used the so-called virtual pot model in which each Partner funding agency will fund its own share of a particular project according to the rules and regulations usually employed when financing their national projects.

Within the Pierre Auger Collaboration a consortium was formed to propose studies for a next-generation cosmic ray experiment and the utilization of new innovative detection methods. These are principle elements of the ASPERA/ApPEC roadmaps. ApPEC is the interest group of the Astroparticle Physics European Coordination [24]. The AugerNext Consortium is formed by

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– Martin Erdmann, RWTH Aachen, Germany   co-applicant
– Karl-Heinz Kampert, University of Wuppertal, Germany   co-applicant
– Ad M. van den Berg, KVI Groningen, The Netherlands   co-applicant
– Zbigniew Szadkowski, University of Lodz, Poland   co-applicant
– Henryk Wilczynski, Inst. of Nuclear Physics PAN, Cracow, Poland   co-applicant
– Antoine Letessier-Selvon, IN2P3/CNRS, France   co-applicant
– Mario Pimenta, LIP - Lab.de Instr.e Fisica Exp. de Particulas, Portugal   co-applicant
– Enrique Zas, University of Santiago de Compostela – USC, Spain   co-applicant
– Valerio Verzi, INFN Roma Tor Vergata, Italy   co-applicant
– Iliana Brancus, IFIN-HH Bucharest, Romania   co-applicant
– Masahiro Teshima, MPI fur Physik, Munchen, Germany   associated partner
– Martina Bohacova, Inst. of Physics - FZU, Prague, Czech Republic   associated partner.

The consortium is open for further participants. First contacts have already been established with, e.g., Russian groups with the aim of common achievements in the radio detection technique at the Tunka experimental site in Siberia [25], or in developing new types of robust scintillation detectors at the INR in Moscow [26].

Beside the Pierre Auger Collaboration providing the scientific and technical environment for the AugerNext project and beside the engaged students working on the various problems, the AugerNext consortium acknowledges the funding agencies supporting the project. Namely, Bundesministerium für Bildung und Forschung (BMBF 05A2011), Germany; Nikhef, Netherlands; The National Centre for Research and Development (NCBiR), Poland; Centre de Calcul IN2P3/CNRS, France; Fundação para a Ciência e a Tecnologia, Portugal; Ministerio de Ciencia e Innovación and Consolider-Ingenio 2010 (CPAN), Spain; Istituto Nazionale di Fisica Nucleare (INFN), Italy; and Romanian Authority for Scientific Reseach, UEFICDI, Ctr.Nr.1/ASPERA2 ERA-NET, Romania.

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