Status of the AugerPrime upgrade of the Pierre Auger Observatory

Nataliia Borodai [1] for the Pierre Auger Collaboration[2, 3, 4]

[1] Institute of Nuclear Physics of Polish Academy of Science, Radzikowskiego 152, Kraków, Poland
[2] Full author list: https://www.auger.org/archive/authors_2021_05.html
[3] Pierre Auger Observatory, Av. San Martín Norte 304, Malargüe, Mendoza, Argentina
[4] spokespersons@auger.org

E-mail: nataliia.borodai@ifj.edu.pl

Abstract. The Pierre Auger Observatory consists of a detector system to study ultrahigh-energy cosmic rays. These cosmic rays can be detected only through the observation of extensive air showers. The hybrid detection of air showers at the Observatory is based on the Surface Detector (SD) – an array of about 1660 water-Cherenkov detectors, and the Fluorescence Detector, with 27 telescopes overlooking the SD. Recently, an upgrade of the Observatory was initiated, called AugerPrime. The main purpose of the upgrade is to improve the mass composition sensitivity of the SD through precise measurements of the muonic and electromagnetic components of extensive air showers. For this purpose, additional scintillator and radio detectors are being installed on top of SD stations. The upgrade also includes updated SD electronics, and underground muon detectors. In this talk, the motivation and the current status of the upgrade will be reviewed.

1 Introduction

Cosmic particles with energies above 10^{18} eV are known as ultrahigh-energy cosmic rays. These particles are extremely rare: an estimated arrival rate of the particles with an energy of above 10^{20} eV is around 1 particle per km^2 per century. The Pierre Auger Observatory [1] is a detector with an area of 3000 km^2, situated in Malargüe, Argentina. It was built to detect the rare cosmic rays by recording extensive air showers, i.e., cascades of secondary particles induced by cosmic-ray particles in the atmosphere. Such a huge detector is aimed to answer the questions of the origin of the cosmic rays of the highest energies, their composition, source distribution, and propagation. The observatory already largely contributed to our understanding of these puzzles. At the same time, the results obtained by the Pierre Auger Observatory indicate the need for an improvement of the measuring capabilities of the existing detectors, where the key feature to be improved is the separation of the muonic and electromagnetic components of air showers. AugerPrime is the ongoing upgrade of the Pierre Auger Observatory, which has been designed for this purpose.

2 The Pierre Auger Observatory

Extensive air showers are registered at the Pierre Auger Observatory with the use of several detection methods. Basic ones include the Surface Detector (SD) array and the Fluorescence Detector (FD). Water-Cherenkov Detector (WCD) stations of the SD array cover the whole area of the Observatory. The principle of operation of the WCD station is based on Cherenkov light emission in water. The WCD stations are sensitive to secondary particles of extensive air showers as they reach the surface of the Earth, providing information on their arrival times and on the lateral distribution of the extensive air shower. The FD consists of 27 telescopes in four sites recording the fluorescence light emitted by the atmospheric nitrogen molecules excited by the shower particles as they traverse the atmosphere. The FD provides data on the longitudinal development of the extensive air showers. The combination of the SD and FD detection systems enhances the reconstruction capability of the Observatory and enables measurements in the "hybrid mode", when the showers are simultaneously detected by the FD and the SD. Other components of the Pierre Auger Observatory are described in detail in [1]. They also include a denser array of WCD, the Auger Engineering Radio Array, prototype underground muon detectors, and atmosphere monitoring facilities.

The Pierre Auger Observatory largely contributed to a number of scientific puzzles. Among the main scientific results of the Observatory are: the identification of several important features of the spectrum of ultrahigh-energy cosmic rays [2, 3] (the high-energy suppression above an energy of 5×10^{19} eV, the "ankle" – a feature at energy 5×10^{18} eV, the observation of the second knee above 10^{17} eV), studies of mass composition of the primary cosmic rays [3] (observation of lighter composition up to 2 EeV and heavier above this energy), observation of a large-scale anisotropy [4] in the arrival directions of cosmic rays above 8 EeV indicating that they are indeed of extragalactic origin. Other significant results reported by the Pierre Auger Collaboration are: a deficit in the number of muons predicted by the hadronic models [5]; search for neutrinos and photons [6]; study of atmospheric phenomena ELVES [7], which are transient luminous events produced at the base of the ionosphere by the intense electromagnetic pulses emitted during lightning discharges.

3 AugerPrime: the upgrade of the Pierre Auger Observatory

Although many findings have been done by the Pierre Auger Collaboration, several old and new problems are still open. It is expected that the AugerPrime upgrade [8,9] will help us in solving these puzzles.

3.1 Motivation for the upgrade

The determination of the mass composition of the primary cosmic rays is a major experimental challenge to be performed in AugerPrime. A more precise estimation of the mass of primary particles on an event-by-event basis with high statistics is required to reach the upper end of the spectrum. It is important to study the number of muons in the shower, which is a good indicator of the primary particle mass. To perform this task, disentangling the muonic and electromagnetic components of the extensive air shower at the ground is needed. This can be achieved with the upgraded detectors of the Observatory. For a full understanding of the observations, a combined analysis of the spectrum and the composition is required. AugerPrime will allow us to measure the composition-discriminated flux in the range from about 10^{18} eV up to the highest energies. It is also expected that it will be possible to understand the muon deficit in shower simulations using the new data from AugerPrime. Testing our understanding of hadronic interactions at c.m.s. energies near and beyond 60 TeV also will be possible with the AugerPrime data. Although anisotropies in the arrival directions have been found, the search for the possible sources of ultrahigh-energy cosmic rays is still not concluded. AugerPrime will allow us to carry out composition-enhanced anisotropy searches based on event-by-event estimates of the primary mass. Among other important analyses, which can be performed based on AugerPrime data, are the search for a proton contribution in the flux suppression region above an energy of 5×10^{19} eV and for ultrahigh-energy secondary photons produced in or near cosmic-ray sources.

3.2 Components of AugerPrime

AugerPrime includes new detectors and upgraded electronics [8,9]: Surface Scintillator Detectors (SSD) – thin plastic scintillator detector planes, designed for a complementary measurement of the shower particles; Underground Muon Detector (UMD) – an array of scintillator detectors buried in the region of the infilled array at a depth of 2.3 m, that will provide direct muon measurements, enabling the verification of the methods used for extraction of muon information obtained with the SSD and WCD complementary measurements; AugerPrime Radio Detector (RD) – antennas, added to each SD station for radio detection of cosmic-ray showers, that will allow for better measurements of inclined

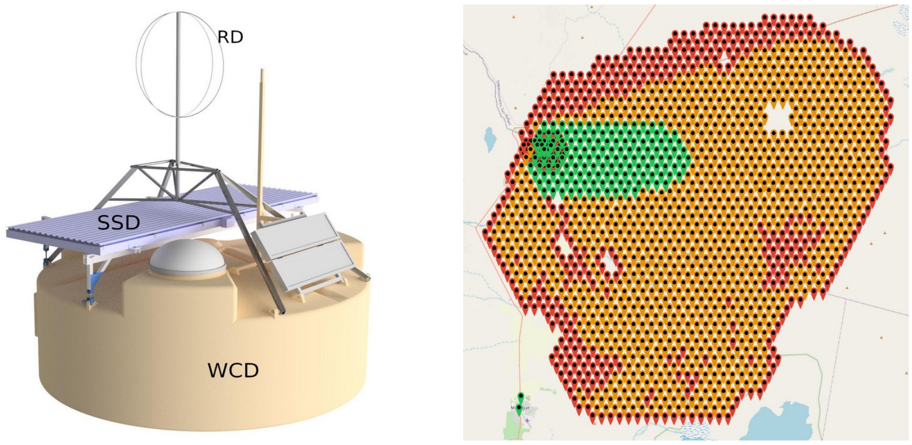
Journal of Physics: Conference Series **2374** (2022) 012043 doi:10.1088/1742-6596/2374/1/012043

showers; new electronics [9] provided by an Upgraded Unified Board (UUB) – upgraded electronics of each SD station will process both WCD and SSD signals, provide faster sampling of traces, better timing accuracy, increased dynamic range, and enhanced triggers; to increase the dynamic range, each WCD will be equipped with an additional “small PMT” – a smaller low-gain photomultiplier tube (PMT) will be installed in SD stations for registration of large pulses that saturate the signal of the large PMTs. In addition, the FD operation mode will be changed to extend measurements into periods with higher night-sky background and twilight, so increasing the duty cycle of the FD from 15% to over 20%.

3.3 Status of AugerPrime and first SSD data

The key element of the upgrade is the installation of new SSD detectors on top of most of the existing WCD detectors. The SSD and the WCD have different responses to muons and electromagnetic particles, therefore providing complementary measurements of the shower particles. All of the 1518 SSDs have already been built and tested at laboratories in Germany, Italy, Poland, France, and the Netherlands. At present, all SSDs are at the Observatory site, where they are being assembled and installed in the field, the WCDs are ready to receive the small PMTs and new electronics. The SSD detectors already installed operate smoothly and show good stability. The electronics is in the testing and production phase. More than 80 UUBs are already installed in the field, and 400 UUBs are awaiting shipment. The performance of the boards is stable and within design requirements. Twenty-four UMD stations are also being deployed (that is 35% of the whole UMD array) and are already taking data. The first measurements of radio signals from air showers performed by installed RD confirm that the data are of a satisfying accuracy.

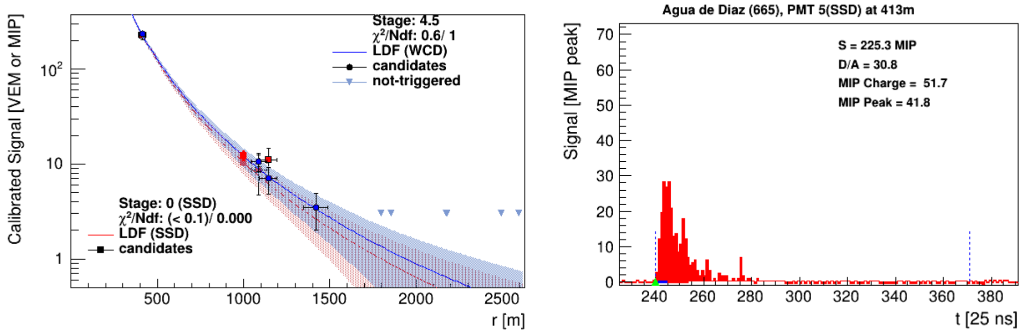
A prototype of an upgraded SD station is shown in figure 1a. It consists of three detector types: WCD, SSD, and RD. SSDs, the new electronics, and the radio antennas are being deployed over the SD stations, with minimal impact on the continuous data taking. A map presenting the status of the deployment of SSD detectors is shown in figure 1b.



(a) (b)

Figure 1. (a) – A prototype of upgraded Auger Surface Detector. (b) – Map presenting the status of the deployment of SSD detectors. The larger fraction of the SD array is orange on the map, that means that 1212 WCD have already SSD installed and 153 (green area) are equipped with PMTs and are in data acquisition.

An example of the first data from AugerPrime SSD detectors is shown in figure 2. The event is an extensive air shower with energy 2.20 EeV and zenith angle 25.17 º, measured with both WCD and SSD detectors. The lateral distribution of a recorded signal vs core distance r is shown in figure 2a. Signal traces for this shower measured by the SSD detector in the SD station named "Agua de Diaz" are shown in figure 2b. After upgrading, a multi-hybrid cosmic-ray detection [8] of events will be available. This means the possibility of simultaneous measurement of an extensive air shower with WCD, SSD, RD, UMD, and FD detectors.



(a) (b)

Figure 2. Example of a real WCD-SSD event with energy 2.20 EeV and zenith angle 25.17 º. (a) – lateral distribution of a recorded signal in VEM (Vertical Equivalent Muon) for WCD and in MIP (Minimum Ionizing Particle) for SSD detectors vs core distance r; (b) – signal traces for SSD.

4 Conclusion

The Pierre Auger Observatory has been operating smoothly with almost full aperture and has already collected more than 15 years of data. It also contributed to the cosmic-ray shower physics, high-energy particle interactions, studies of the atmosphere, and development of new instruments.

The AugerPrime upgrade of the Observatory is now underway. At present, 100% of the SSD modules have already been built, with 80% of them installed in the field, and most of the remaining SSDs are already at the Observatory site, ready to be deployed. Their PMTs are being shipped to the site after testing in Europe. The new electronics and small PMTs are mainly in the production and testing phases. The UMD and RD AugerPrime detectors are already in testing and deployment phases. The performance of the installed AugerPrime detectors is stable, allowing for detection of the first air showers. AugerPrime is expected to be completed in 2022.

After completion, the AugerPrime upgrade of the Observatory will deliver multi-hybrid measurements of cosmic-ray showers using all the surface detection techniques, allowing for simultaneous measurement of a shower with water-Cherenkov detectors, surface scintillator detectors, radio detectors, muon counters, and fluorescence detectors. Operation of the upgraded Observatory is foreseen for at least 10 years, nearly doubling the statistics with respect to the presently available one.

5 References

1 The Pierre Auger Collaboration 2015 *Nucl. Instrum. Meth.* A **798** 172-213
2 The Pierre Auger Collaboration 2020 *Phys. Rev.* D **102**, 062005
3 The Pierre Auger Collaboration 2019 *Preprint arXiv:* 1909.09073
4 The Pierre Auger Collaboration 2017 *Science* **357** 1266
5 The Pierre Auger Collaboration 2020 *Eur. Phys. J.* C
6 R. Engel, D. Seckel and T. Stanev 2001 *Phys. Rev.* D **64** 093010
7 The Pierre Auger Collaboration 2020 *Earth Space Sci.* **7** e2019EA000582
8 The Pierre Auger Collaboration September 2020 The Pierre Auger Observatory and its Upgrade *Science Reviews – from the end of the world (Argentina)* vol 1 no 4 pp 8-33
9 The Pierre Auger Collaboration 2016 *Preprint arXiv:*1604.03637
10 T. Huege and the Pierre Auger Collaboration 2019 *EPJ Web Conf.* 210 05011

Acknowledgments

The successful installation and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the staff in Malargüe, and the financial support from a number of funding agencies in the participating countries, listed at https://www.auger.org/index.php/about-us/funding-agencies. In particular, we want to acknowledge support in Poland from National Science Centre grant No.3992016/23/B/ST9/01635, and grant No. 2020/39/B/ST9/01398, and from Ministry of Education and Science grant No. DIR/WK/2018/11.