AugerPrime: the Pierre Auger Observatory upgrade

Gioacchino Alex Anastasi,
on behalf of the Pierre Auger Collaboration

15th Pisa Meeting on Advanced Detectors
La Biodola, 22-28 May 2022
Hybrid detection of extensive air showers

Array of water-Cherenkov tanks
- 1600 in a 1.5 km grid of 3000 km²
- 61 in a 750 m grid of 30 km² (Infill)

Fluorescence telescopes (FD)
- 24 in 4 buildings overlooking the array - elevation 0°-30°
- 3 overlooking the Infill (HEAT) - elevation 30°-60°

Engineering array of underground muon detectors (AMIGA) in the Infill area.

Array of radio antennas (AERA)
- 153 stations covering ~17 km²

Around the center of the array: monitoring & laser facilities
More than 15 years of data and results

- Flux suppression well established: effect of propagation (GZK effect) and/or maximum acceleration at sources?
- Composition mixed and heavier above ~2x10^{18} eV from X_{max} measurements … but statistics too low above ~10^{19.5} eV due to FD duty cycle ~15%.
- Large scale dipolar anisotropy (6.6 σ): extragalactic origin for UHECR > 8 EeV +
  Hints of correlation with SBG/AGN directions for UHECR > 40 EeV ➟ Quest for sources still open.
- Muon puzzle: muon content in simulations lower than in data
  Tension with all hadronic models.
- … and many more
AugerPrime scientific case

Primary goal: mass composition of UHE

- to study the origin of the suppression
- to accomplish composition-driven anisotropy analyses *e.g. if 10% of protons at the highest energies*
- to study the hadronic interactions at energy much larger than human made accelerators (hints of new physics?)
- to provide better estimates of $\gamma$ and $\nu$ flux (explore potential of future experiments)

Scenario 1: maximum rigidity model
Scenario 2: photo-disintegration model
The upgrade of the Observatory

**Surface Scintillator Detector (SSD)**

different response to electromagnetic & muonic shower components w.r.t. WCD

**Radio antenna**

to measure the radio emission of showers in atmosphere (30-80 MHz)

**Underground Muon Detector (UMD)**

direct muon measurement and cross-check of SSD-WCD combined analysis

**Small PMT (SPMT)**

increase of the dynamic range of WCD measurements

**Upgraded Unified Electronics (UUB)**

to process the signals from all the new detectors with improved performances

*Auger Preliminary Design Report [arXiv:1604.03637]*

A. Castellina, EPJ Web of Conf.210 (2019) 06002
The Scintillator Surface Detector (SSD)

Large-scale production of >1500 SSDs and installation completed.

Preproduction array of 77 SSDs with PMTs running since March 2019: long-term performances in G. Cataldi, PoS(ICRC2021)251

1.5-inch bi-alkali PMT (Hamamatsu R9420)

Each SSD is mounted above a WCD (in slave-trigger mode) to disentangle the muonic and e.m. components
The Underground Muon Detector (UMD)

73 positions in the Infill area, each with 3 modules of 10 m²

2.3 m underground
- e.m. component of the shower (e±, γ) absorbed
- direct measurement of muon density

Each module: 64 scintillator strips with wavelength-shifting optical fiber coupled to an array of silicon photomultipliers (SiPMs)

Two acquisition modes:
- **Binary mode** (64 traces) to count single muons
- **ADC mode** (64 SiPM signals summed) to measure a high number of muons in EAS
The Radio Detector array (RD)

- measurement of e.m. component in inclined showers (zenith > 60°) via radio emission
  - complementarity with SSD+WCD
  - complementarity with UMD (low energy region)
- ~300 km² of RD equals the yearly exposure of FD
  (duty cycle RD ≳ 95% vs FD ~ 15%)

For technical details and expected performances:
Bjarni Pont, PoS(ICRC2019)395
Felix Schlüter, PoS(ICRC2021)262

World-largest radio detector for extensive air showers at UHE.
Huge exposure for horizontal events.

1661 dual-polarized Short Aperiodic Loaded Loop Antennas (SALLAs)
1.2 m diameter, mounted on top of each WCD (slave-trigger mode).

electromagnetic component
hadronic component
muonic component
radio emission
atmosphere
ground
cosmic ray
E. Holt
The Small PMT (SPMT)

Hamamatsu R8619 1-inch diameter PMT
Linearity and gain curves of each SPMT carefully measured (M. Buscemi et al., 2020 JINST 15 P07011)

New HVPS module (A7501B) developed by CAEN & INFN-Torino
Validation of 1600+ unit (G.A. Anastasi et al., 2022 JINST 17 T04003)

Active SPMT area ~1/100 of the 9-inch WCD PMTs
direct measurement of (very large) density of particles up 200-300 m from the shower core.

LPMT window
hole in the stabilizer disk for the SPMT

> 20,000 VEM

\[
\begin{align*}
&10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \\
\text{lg(S/VEM or MIP)} &\quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5
\end{align*}
\]
The Upgraded Unified Electronics (UUB)

On a single board:
- analog signal processing, triggering, calibration (WCD + SSD PMTs),
- interface with UMD and RD systems,
- GPS time tagging, data acquisition and communications via radio transmitter.

With respect to old electronics:
- faster ADCs (40 → 120 MHz)
- larger dynamic range (10 → 12 bits)
- significantly more powerful FPGA
- upgraded CPU (> 10 times faster)
- backwards-compatibility
  (fit the enclosure of current electronics + accept the existing PMT, GPS antenna and communication cables)

Technical details in
G. Marsella, PoS(ICRC2021)230

Manufacturer test (SITAEL company)
- automated optical inspection
- semi-automatic test bench
  (installation of operative system + full functionality test)

Environmental Stress Screening test @ Institute of Physics, Prague - details in M. Bohacova, PoS(ICRC 2019) 199
Measurements with AugerPrime

Simultaneous measurement of a shower with WCD, SSD, RD, UMD (& fluorescence telescopes)

- top-down method (i.e. comparison with MC)
- radio observables (e.g. LDF slope, wavefront shape)
- comparison with muon density from UMD (lower energies)

+ RADIO

AugerPrime

15th Pisa Meeting, 23/05/2022
Conclusions

**AugerPrime**:
- largest exposure detector for UHECR with composition sensitivity above $4 \times 10^{19}$ eV
- ★ Deployment and commissioning to be completed by mid 2023.
- ★ Data taking foreseen up to 2030.
- ★ Fundamental input for future experiments.
Backup
Deployment status

UMD deployment and commissioning currently on-going at a pace of 2 stations per month

- SSD installed (1437 detectors)
- with PMT (356 detectors)
- w/o PMT (1081 detectors)
- SSD not installed (230 detectors)
- UUB (372 detectors) + SPMT

PoS(ICRC2021)233
Calibration performed using atmospheric muon signals acquired by dedicated triggers.

**WCD PMTs unit : VEM**  
Vertical Equivalent Muon

**SSD PMT unit : MIP**  
Minimum-Ionizing Particle

About 40% of WCD calibration triggers produce a MIP in the SSD.

All SSD tested with cosmic-ray muons:
(i) to check the light tightness;
(ii) to determine the response to a reference minimum-ionizing particle

Left: average logarithm of the deposited charges in 1 cm × 1 cm bins for one SSD as measured in a muon tower.

- First peak: low energy e⁺, γ  
- Second peak: VEM estimate

- First peak: pedestal (integral of baseline)  
- Second peak: MIP estimate
Reconstructed muon densities $\rho_{35}$ VS energy $E$ (estimated using the WCD data alone)

Muon lateral distribution function (MLDF)

$$\rho(r, E, \theta) = \rho(450) \cdot f(r, \theta)$$

Schematics of the laboratory setup (left) used to characterize the UMD traces and average traces (right) for the binary and ADC modes, measured at different optical-fiber lengths

First direct measurement of muon densities $\rho_{35}$
Radio emission not absorbed in atmosphere
- signals depends on the source distance and not on the amount of traversed matter

Radiation strongly forward-beamed into a cone of few degrees:
- vertical shower: small footprint, strong signals
- inclined shower: large footprint, weaker signals

Nearly full efficiency for $\theta \gtrsim 70^\circ$ at high energies

End-to-end pilot calibration using the Galactic radio emission
( Tomáš Fodran, PoS(ICRC2021)270 )

Target: absolute calibration of the Radio Detector
- Measurement of power as a function of frequency and local sidereal time (LST), separately for the EW and NS channels.
- Simulations using different sky temperature map models and different antenna models.
- Comparison to estimate calibration constant and background noise.
Measurements with the WCD 9-inch PMTs limited by electronics saturation: overflow of the anode FADC dynamic range of 4095 channels, occurring for integrated signals \( \gtrapprox 700 \text{ VEM} \).

SPMT extends the dynamic range of WCD up to > 20,000 VEM. Only stations < 300 m from the core (and at very high energies) are expected to saturate.

Station closest to the core saturated in more than 40% of events above \( 3 \times 10^{19} \text{ eV} \).

Expected maximum SPMT signal without saturation for a subset of stations, estimated using locally selected small showers signals.

The WCD and SSD dynamic ranges must be similar to benefit the most from the combined information.

Signals reconstructed in the WCD and in the corresponding SSD.
Radio emission mechanism

The 30–80 MHz band is used by most experiments. Due to coherence effects, the cosmic-ray-induced radio emission is strongest below 100 MHz. Atmospheric noise and short-wave band transmitters make measurements below 30 MHz unfeasible. From 85 to 110 MHz the FM band interferes with measurements.

Geomagnetic emission

- geomagnetic field deflects e- and e+ in opposite directions —> transverse current varying over time
- linear polarisation of the radiation (E aligned along the Lorentz force)
- propagation along the shower axis

Askaryan effect

- ionisation of ambient medium by EAS particles: e+ annihilation —> excess of e- along the longitudinal development
- linear polarisation of the radiation (E radially oriented wrt EAS axis)
- sub-dominant in EAS