Radio detection of extensive air showers at the Pierre Auger Observatory

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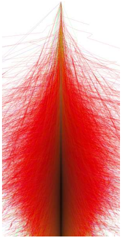
Outline

Physics motivations

Ultra High Energy Cosmic Rays (UHECR)

- most energetic source of elementary particles available to scientists macroscopic energies E > 1 EeV (10^{18} eV)
- but very low flux !

$\Rightarrow$ Understanding their nature and their origin is the objective of the Pierre Auger Observatory



Extensive air shower (EAS)

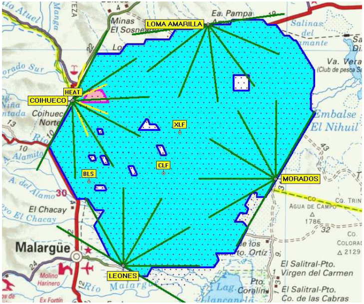
- UHECR produce large shower of particles in Earth's atmosphere (calorimeter)
- cosmic particle characteristics obtained from the measured properties of extensive air showers

Pierre Auger Observatory: an hybrid detector

- longitudinal development with fluorescence light telescopes
- lateral spread at ground level with ground based particle detectors

The Pierre Auger Observatory

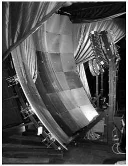
The largest cosmic ray detector in operation



Data taking started in 2004, detector completed in 2008

- 3000 km^2 in pampa Amarilla, Argentina
- surface detector (SD)
  - 1660 water Cherenkov detectors, triangular grid 1500 m spacing
  - $\sim$ 100% duty cycle

- fluorescence detector (FD)
  - 27 optical telescopes in 5 buildings
  - $\sim$ 13% duty cycle



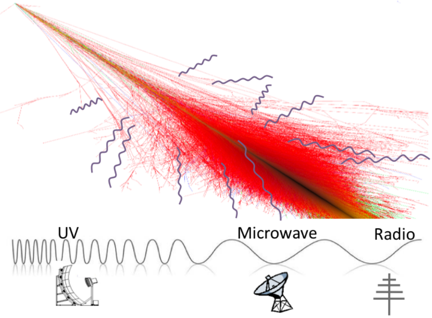
Data and results

- high quality data in stable and continuous operation
- measurements of the UHECR above 1 EeV with unprecedented sensitivity

Aims of the radio detection

- enhance the capabilities of the Observatory in determining the UHECR mass composition
- study the requirements for a very large aperture detection system in the next generation of air shower arrays

Electromagnetic waves from air shower



- several emission processes
- different λ ranges

Advantages of the radio detection

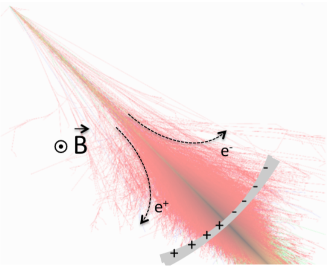
- high duty-cycle
- cost-effective approach

Radio detection in the MHz range

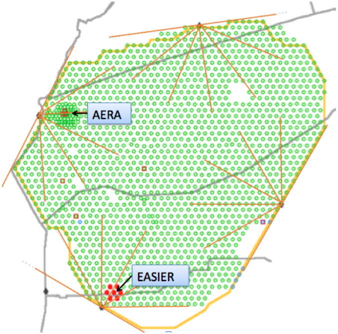
Radio detection of atmospheric shower

Recent progresses in EAS radio detection and simulation techniques

- MHz emission beamed in the propagation direction of the shower
- Broadband radio pulses from EAS coherent in 10−100 MHz
- LOPES and CODALEMA: antennas triggered by particle detectors
  - to demonstrate the feasibility of radio detection
  - dominant emission mechanism due to the deflection of electrons and positrons in the Earth's magnetic field



Radio-detection at the Auger Observatory



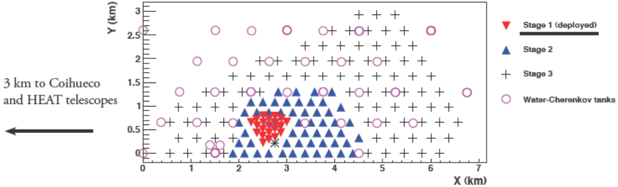
Goals of the AERA project

1. calibration of the EAS radio emission, including sub-dominant mechanisms
2. physics capabilities of the radio technique at a significant scale
3. measurement of the CR composition from 0.3 to 5 EeV: transition from Galactic to extra-Galactic CR.

Technical challenge: develop a large-scale, autonomous antenna array, triggering directly on the radio pulses.

AERA site within the Observatory array

- possibility of EAS detection in coincidence with SD / FD ⇒ calibration of the radio signals.
- first stage: 24 radio detector stations set on a 150 m grid.

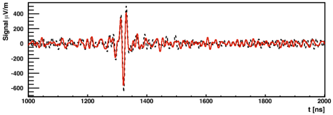


Autonomous radio detector station

- log-periodic dipole antenna, dual-polarization (NS and EW)
- analog and digital readout electronics
- autonomous power system (solar panel+batteries)
- high-speed fiber-optical communications link

sensitive between 27 and 84 MHz ($\sim$ radio quiet region).

First physics results



Complete description of AERA, first physics results and improvements for the next stage $\rightarrow$ M. Kleifges's poster at the poster session

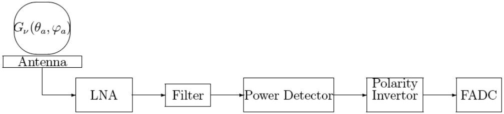
EASIER: Extensive Air Shower Identification using Electron Radiometer

Goals of the EASIER project

1. upgrade existing particle detectors with a technique providing essential complementary information.
2. based on the existing hardware : antenna totally enslaved to the station
3. same triggering, timing and power supply system as the station

MHz detection

- 7 stations equipped to validate the setup
- fat dipoles, EW polarization, set at top of a 3 m plastic tube
- filtering : 30-80 MHz



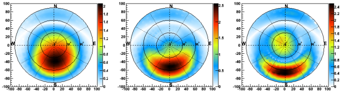
Radio signals detected in MHz range

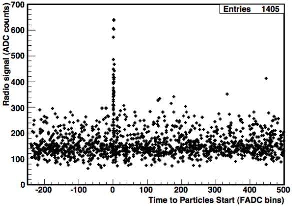
$\lesssim$ 4 months of running

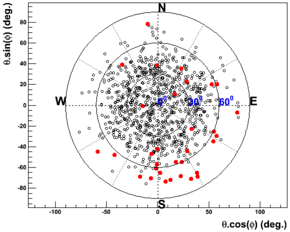
- 36 events in clear time coincidence with particle arrival time
- E$>$ 0.4EeV (measured by the SD)

North-south asymmetry

- Excess of events from the south
- Geo-magnetic field + antenna lobe patterns.





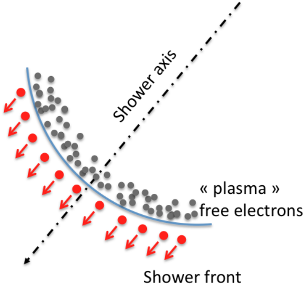


Such setup: very simple way of studying MHz emission at large distances and at energies above 1 EeV.

Microwave detection of cosmic ray air showers

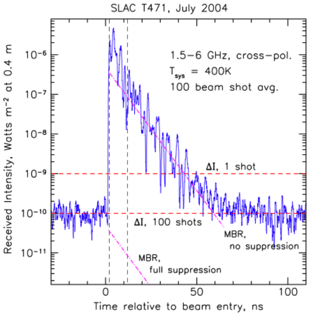
Molecular Bremsstrahlung Radiation (MBR)

- EAS charged particles → ionization → plasma
- Free electrons interact with air molecules → Bremsstrahlung emission in microwave regime
- unpolarized and isotropic emission
- scaling with no. of secondary charged particles



Initial beam measurements

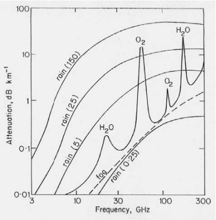
- SLAC T471 experiment - Gorham et al. Phys. Rev. D78 (2008)
- GHz emission observed from electro-magnetic cascades in anechoid chamber



Microwave emission

Potential for an FD-like detection technique

- observation of the shower longitudinal development
- nearly 100% duty cycle
- low background and limited atmospheric effects: microwave absorption $\lesssim 0.05$ dB/km
- low cost (satellite TV) $\rightarrow$ ability to cover large area



Several issues to be clarified

- spectral intensity of this microwave radiation (MBR yield)
- scaling with the primary energy (linear or quadratic ?)

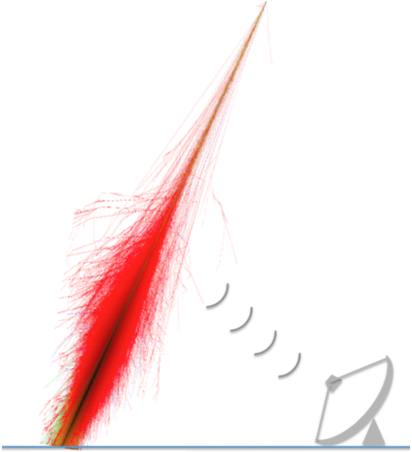
$\rightarrow$ New generation of experiments: Amy@Frascati, Maybe@Argonne

Microwaves detection at the Pierre Auger Observatory

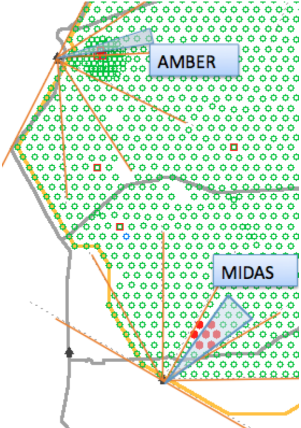
- Essential to detect microwaves in coincidence with shower measurements to relate observed signals to shower parameters
- R & D: complementary prototypes to confirm EAS microwave emission

First approach

Parabolic dish reflector, instrumented with an array of antenna horns

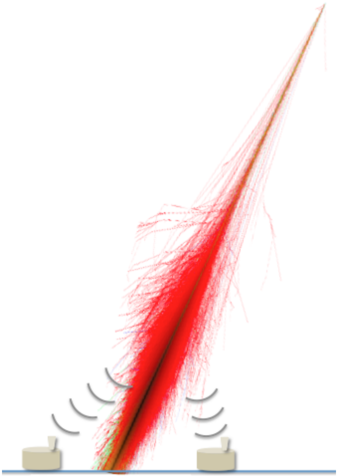


- effective area $\sim 10\ \mathrm{m}^2$
- several kilometers ($\mathcal{O}(10\mathrm{km})$) from the shower.
- Configuration similar to the fluorescence telescope one.

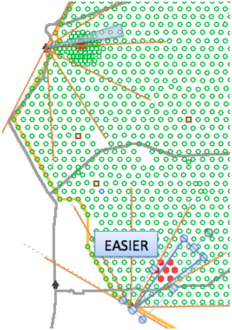


Second approach

Feed horns located on each surface particle detector



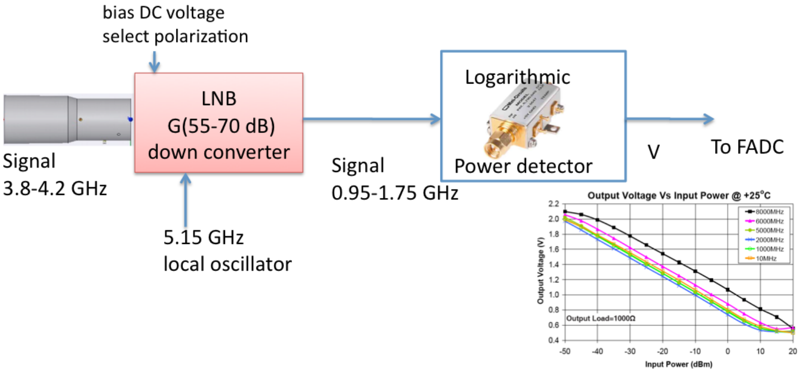
- small effective area ($\mathcal{O}(0.003\mathrm{m}^2)$)
- large field of view (60°)
- within $\sim$ 3 km from the maximum of the shower development.
- radio signal compressed in time.



Instrumentation to detect microwaves

Available satellite communication hardware

- in the C-band (3.4 GHz—4.2 GHz)
- in the Ku-band (10.7 GHz—12.7 GHz)



AMBER receiver

- 2.4m off-axis parabolic reflector, optical axis 30 in elevation
- 4 dual polarized dual band feed horns (C-band and Ku-band),
- 12 single polarization C-band horns
- (FoV) of $7^\circ \times 7^\circ$.

Calibration procedure (University of Hawaii)

- Inject fixed power into each power detector, measure output
- calibrate noise figure of each LNB (using a liquid nitrogen cold load and RF absorbing material inside an anechoic chamber)
- calibrate dish noise using a calibrated LNB

T_{sys}: C-band: from 45 K for the interior to 65 K for the exterior ring
Ku-band: 100 K (Ku LNB : higher system temperature)

Observation of Sun transits

Validation of the expected performance (pointing, alignment, focus)

AMBER at the Pierre Auger Observatory

At the Coihueco FD, alongside the High Elevation Auger Telescopes (HEAT) overlooking the SD "infill" array

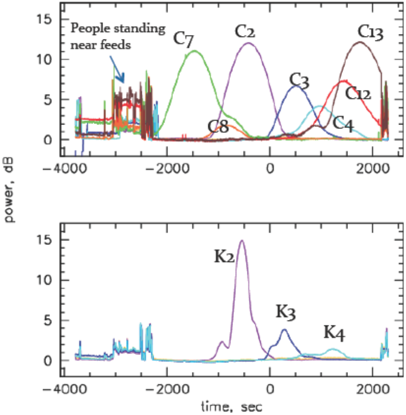
External trigger

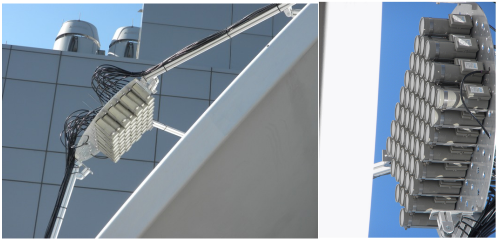
- from the SD, average latency of 3 s.
- ADC: very large circular buffer (5 s) to hold the digitized (100 MHz rate) trace
- shower geometry of triggered events cross-checked with the AMBER FoV
- EAS is confirmed to be within the FoV $\rightarrow$ 100 μs of data stored for offline analysis.

Expected rate

- 3 events per month with an energy threshold at 1.6×10^{18} eV, with a quadratic scaling scenario.

Crab nebula and Sun scans confirm the estimated microwave sensitivity of AMBER



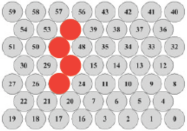


MIDAS receiver

- 4.5 m parabolic reflector
- 53 pixel camera arranged in 7 rows of 7 or 8 pixels
- C-band feeds, $2^\circ \times 2^\circ$
- total of $20^\circ \times 10^\circ$

Self-triggering system

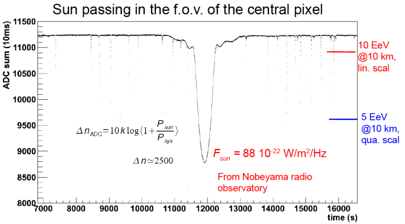
- First Level Trigger: pixel threshold trigger → running sum on a 1μs compared to a self-regulating threshold → FLT rate kept at 100 Hz.
- Second Level Trigger: pixels (at least 4) with FLT in time coincidence and pattern compatible with an EAS pattern topology
- 100 μs of ADC trace readout when SLT issued



Calibration (University of Chicago)

- Relative: Log-periodic calibration antenna at center of dish, connected to a 4 GHz RF pulser
- Absolute: observation of Sun, Moon and Crab nebula transits
- Consistent $T_{sys} \sim 100$ K

⇒ EAS detectability down to $E_{\rm sh} = 10^{18}$ eV, even if linear scaling



Data taking in Chicago

- 3 months $\rightarrow$ quadratic scaling with E_{sh} of the microwave emission excluded
- Some 4 pixels candidates but difficult background estimation

MIDAS at the Pierre Auger Observatory

Camera and its electronics to be installed on a 5 m parabolic reflector at the Los Leones FD site, overlooking the SD array and EASIER.
quieter RF environment $\Rightarrow\sim$ 100% duty cycle

Expected event rate

End-to-end simulation: realistic estimate, given triggering conditions expected to be $\sim$1 event/month for $E_0 > 10^{19}$ eV (linear scaling).

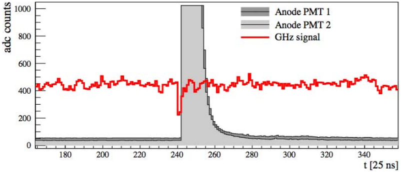
EASIER antenna system

- Upward-facing feedhorn/LNBs + ring + radome
- mounted directly above a SD station
- FoV $\sim 60^\circ$, low T_{sys}
- Trigger from local surface detector station
- Digitization with the existing Flash ADC at 40 MHz, Auger DAQ
- Prototype hexagon (7 stations) equipped in April 2011

EASIER: Extensive Air Shower Identification using Electron Radiometer

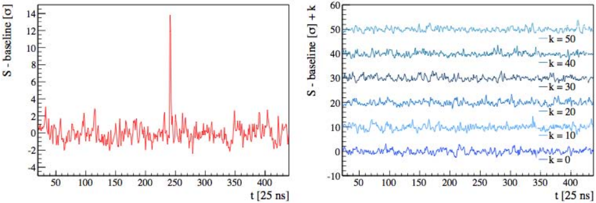
EASIER GHz candidate

- First evidence of GHz radiation from an air shower
- GHz signal $\sim$ 50 ns before the PMT one excludes possibility of emission from the PMT itself.



Event characteristics

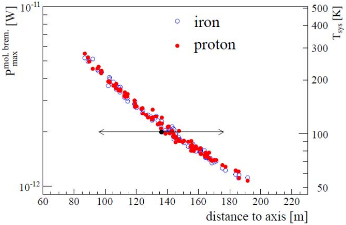
E $=$ 14 EeV, zenith angle $\simeq 30^\circ$, shower core at $\sim$ 140 m of the antenna



signal: 14 σ significance. No signal on antennas of the 6 surrounding stations.

GHz signal origin ?

- Expected MBR signal
  - from MBR yield measured at SLAC
  - using shower profile parametrizations
  - detection system characteristics



- coherent emission that enhances the signal in the forward region cannot be excluded

Origin of this measured signal: cannot be demonstrated to be caused by MBR

Extension of the detection array

April 2012 GHz detection system installed on 61 stations, on 100 km^2.
expected rate: $\sim$ 10 events per year with E$>$ 3 EeV at the 5 σ level

Conclusions

- Numerous advances made by the Pierre Auger Collaboration in detecting and reconstructing radio emission produced by the EAS in the MHz range
- Valuable to plan the future stages of radio-detection arrays

- Strong R&D program to explore the viability of microwave detection as a new method of air shower profile measurement.
- Three complementary detection prototypes installed at the Pierre Auger Observatory
- Goal: characterization of the signal (emission mechanism, scaling, angular distribution,...) emitted in GHz frequency range by EAS
- Use events in coincidence with either the surface detector or the fluorescence detector (or both).

- More data coming soon: EASIER extension, MIDAS@Malargue, AMY test beams....


THANK YOU FOR YOUR ATTENTION
Photographed by Radomir Smida