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GRAND: Status and Perspectives

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The GRAND (Giant Radio Array for Neutrino Detection) is a proposed next-generation observatory of ultra-high-energy (UHE) neutrinos, cosmic rays, and gamma rays of cosmic origin, with energies exceeding 100 PeV. GRAND is a collection of large-scale ground arrays of self-triggered radio antennas that measure the radio emission from extensive air showers initiated by UHE particles. Three prototype arrays are in operation: GRAND@Nançay in France, GRAND@Auger in Argentina, and GRANDProto300 in China. While operating the prototypes and from the data they provide, the detection principle and technology of GRAND are tested, in preparation for its next phase. This will consist of two arrays of 10,000 antennas each, in the Northern and Southern hemispheres, to be deployed from 2028 on. We will present the concept of GRAND, its science goals, the status of the prototypes, their first measurements, and the technical and scientific perspectives that these measurements open for the field.

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1. Introduction

The Giant Radio Array for Neutrino Detection (GRAND) [1] is an envisioned experiment to explore an extensive science case in ultra high energy (UHE) astrophysics. The physics goals range from topics in cosmology and radio astronomy to the detection of UHE messengers through the detection of the electromagnetic emission of their particle cascades in the atmosphere. Of these, the main target is to enable UHE neutrino astronomy, with the discovery of UHE neutrinos in the intermediate deployment stages.

The GRAND Collaboration builds on the experience gained from experiments like LOPES, LOFAR, CODALEMA, AERA and TREND [2–6], where air-shower detection through its radio emission was verified and established as a reliable detection method. The emission is described by two main mechanisms, the geomagnetic effect describing emission from charge deflection in the Earth's geomagnetic field, and the charge-excess effect describing the creation of a moving dipole due to an increasing net negative charge of the shower front. The signal is characterized by transient pulses with a duration of order 100 ns within a frequency range of a few up to hundreds of MHz. The amplitude is detectable when it is 3 to 5 σ above the background level.

The emission can be viewed as point-like around the shower maximum and it is characterized at ground level by the radio footprint. Its size depends on the characteristics of the air shower. Due to propagation effects through the atmosphere, signals from different emission points arrive coherently up to 100–200 MHz, depending on distance from the shower axis. In the shower plane, the Cherenkov ring is a ring-like region, characterized by the Cherenkov angle, where there is maximum coherence. Within this frequency regime, the signal amplitude scales linearly with the primary particle energy, a valuable characteristic for reconstruction efforts.

2. GRAND concept

The main analysis channel of the GRAND Collaboration contains upward going and Earth-skimming tau neutrinos. The tau neutrino interaction underneath the surface of the Earth and/or in a nearby mountain chain produces a tau lepton which decays and creates a particle cascade. The resulting air shower is nearly horizontal and its radio footprint is a few kilometers long. In order to detect the complete footprint and maximize event rates, a large instrumented area is required. Radio antennas are cheap, robust and scalable, making them ideal for these giant arrays.

The Collaboration's plan is a final set of several sub-arrays at favorable sites worldwide, instrumenting an area of over $200,000$ km^2 with 200,000 radio antennas. Such an ambitious goal will be achieved through a staged approach. The first deployment stage started in 2023 with three small prototypes at different sites worldwide. With these setups, it is expected to detect cosmic rays with energies of $10^{16.5}$ to 10^{18} eV, validating autonomous radio detection of inclined and very inclined air showers. The next step will consist of two sites consisting of $10,000$ antennas each, GRAND-North in China and GRAND-South likely in Argentina, foreseen to start by 2028. By then, GRAND is scheduled to be sensitive to a possible discover of EeV neutrinos. Lastly, from the mid to end 2030s, the final GRAND200k stage is envisioned to be operational and capable of performing neutrino astronomy.

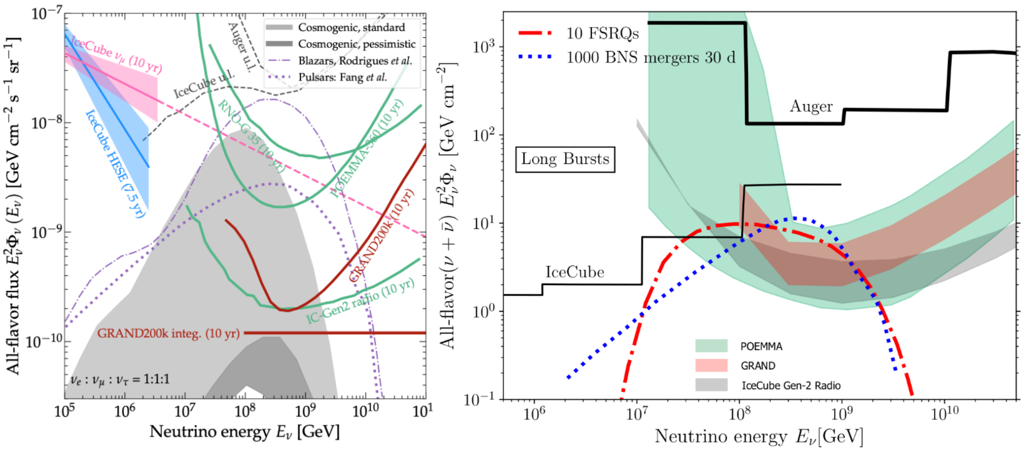

Figure 1: GRAND's and other relevant experiments' sensitivity to the diffuse neutrino flux, on the left, and to the fluence for two types of long burst events, on the right, from [7].

Simulated sensitivity estimates show that the final GRAND setup will be sensitive to both the diffuse cosmogenic neutrino flux and to the instantaneous fluence for short duration astrophysical events [7], see Figure 1. Combined with the expected wide field of view and a sub-degree angular resolution [7, 8], the GRAND experiment has the properties to perform neutrino astronomy. It can also probe for possible transient neutrinos sources of special interest in multi-messenger and multi-wavelength event measurements.

Technical challenges have to be overcome to achieve the final envisioned performances. The deployment through stages assists in solving these, paving the path to the larger arrays. Given that order of thousands of antennas are to be produced and deployed, the detection units need a design which is low cost, robust and has low complexity. The communication and data acquisition must be capable of handling a large data volume and transfer at low rate and low power. Aiming to a low cost array of only radio antennas also requires a validated autonomous triggering on radio signals. Finally, reconstruction methods for very inclined and radio-only air showers must be developed and validated.

3. GRAND status

The year 2023 marked a turning point for the GRAND Collaboration as three prototype arrays were deployed on three different continents: GRAND@Nançay in France, GRAND@Auger (G@A) in Argentina and GRANDProto300 (GP300) in China. The different locations allow to access the adaptability of the GRAND setup to different environments, a requirement for later deployment stages. Also, each prototype array has a set goal, which combined will properly equip the Collaboration to deal with the larger final antenna arrays.

The GRAND setup was deployed at all three sites, with some adaptations to match the local environment and purpose of the prototype. The detection unit consists of butterfly antenna's in three polarization directions named Horizon Antenna, which has a larger sensitivity to events close to the horizon, see the image on the left of Figure 2. The arms are set on the top of a 3.5 meter high pole, which also holds a communication antenna for connection with the data acquisition

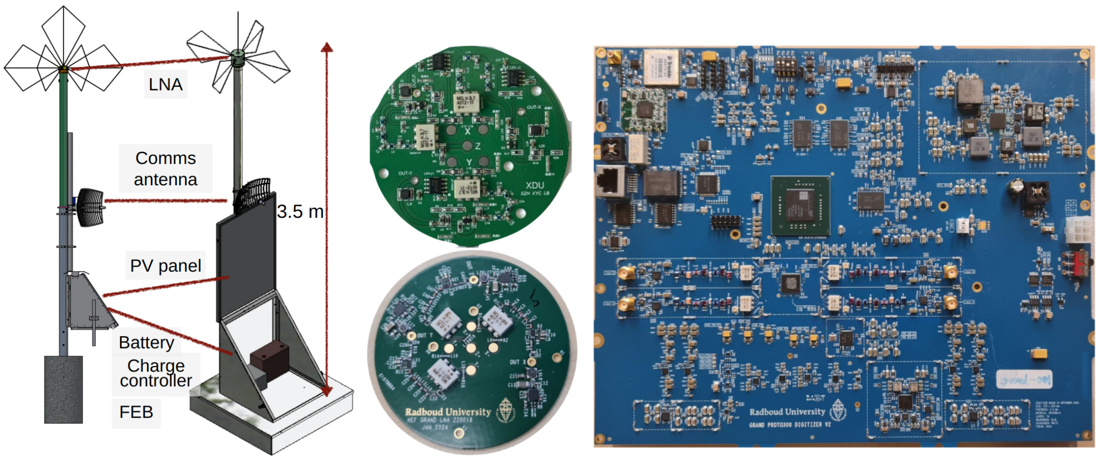

Figure 2: Schematics for GRAND's detector unit, on the left. The antenna arms and the LNA board are connected to the nut on the top of the 3.5 meters pole. Midway through the pole, the communication antenna can be seen. At the bottom, an aluminum box holds the solar panel and stores the battery, the charge controller and the Front End Board (FEB). On the right, the designed GRAND electronics boards. The two LNA boards, for GP300 on top and for G@A on the bottom, are designed to handle the corresponding local environments. The noisier electromagnetic environment in Argentina requires more signal amplification. On the far right, the FEB.

Figure 3: The GRAND detector unit deployed at each of the three prototype sites: GRAND@Nançay on the left, GRAND@Auger in the middle and GRANDProto300 on the right.

computer. The Collaboration has developed its own electronics, for both the Low Noise Amplifier (LNA) board and the Front-End Board (FEB), see Figure 2 on the middle and on the right. An online self-trigger algorithm was implemented, running on three acquisition modes: self-triggered, unbiased trigger and periodic trigger. The prototypes deployment was completed in 2023 after which the commissioning phase began, with the first experimental data being collected.

3.1 GRAND@Nançay

Four GRAND detector units were deployed in the Nançay Radio Observatory, in France. The prototype is too small for physics measurements and was aimed as a test-bench due to its closeness

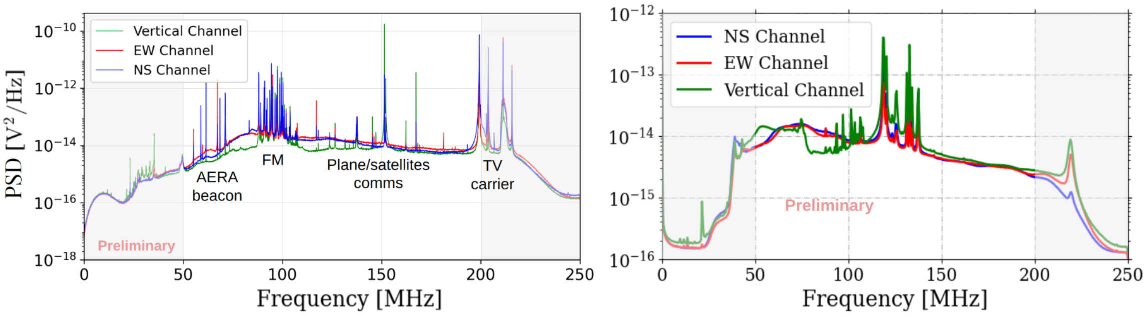

Figure 4: First results from the G@A prototype, left, and from the GP300 prototype, right. For both, averaged Power Spectrum Densities (PSD) from periodic triggered data indicate local background noise. The identification of the observed peaks for the GP300 PSD is on-going.

to European laboratories. Considering limitations of the Observatory, the antenna pole used is smaller than those at the other sites and the communication with the data acquisition computer is done through underground optic fiber cables. An image of the deployed unit can be seen in the left of Figure 3.

3.2 GRAND@Auger

By means of an agreement with the Pierre Auger Observatory (Auger) [15], in Malargüe, Argentina, ten antennas of the Auger Engineering Radio Array (AERA) were repurposed as GRAND detector units, see the center of Figure 3. The prototype allows for validation of GRAND's detection concept with the possibility of cross-calibration with events detected by the surface detector of the Pierre Auger Observatory. The deployment was finalized in August 2023 and, since then, has been taking data with three trigger modes. From random data taken every ten seconds, average power spectrum densities (PSD) are estimated to understand the local electromagnetic background, see Figure 4. Online self-triggered events were also obtained, with up to 7 detection units in time coincidence [9, 11]. In the next stage, a search for air showers in coincidence with the Auger surface detector will be performed. More information on G@A status is given in [11].

3.3 GRANDProto300

The GRANDProto300 prototype is expected to have 300 antennas at its final stage. In February 2023, the first 13 antennas were deployed on the site north to DunHuang, China. The main goal was to validate the GRAND detector units and detection concept. Midway through 2024, the positions for a larger 217 antenna stage were approved and the deployment of 70 more units started in November 2024. The hardware and trigger tests are currently ongoing. The data taking with the 13-antenna array is stable and PSDs are also produced to study the local background, see Figure 4. Self-triggered events with offline coincidence are also collected, aiding to improve the trigger algorithm [9, 10].

4. Preliminary reconstruction efforts

With the first incoming data from the prototype setups, the Collaboration focused efforts on developing new reconstruction methods and establishing a GRAND software pipeline as the

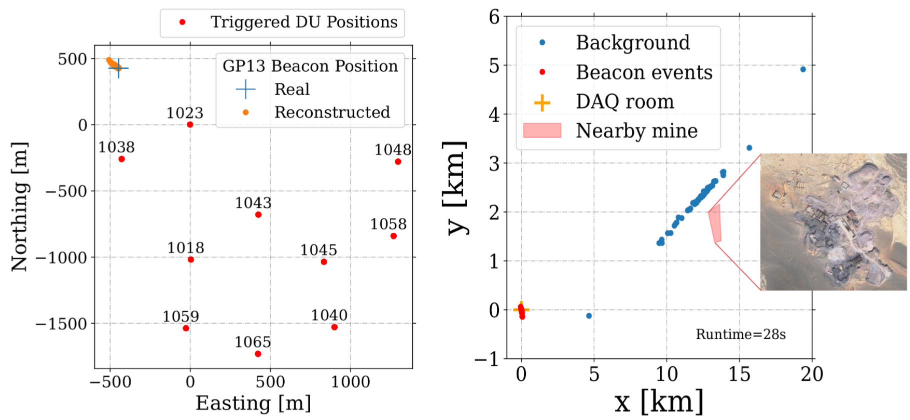

Figure 5: Reconstructed arrival direction for offline coincident events from the GP300 beacon run. The events were reconstructed close to the real beacon position, as can be seen on the top left markers in the image on the left. Some events from the same runs gathered to a location far off the array, which was correlated to the position of a nearby mine, as depicted on the right.

Collaboration's analysis tool. GRANDlib [12] is a Python-based library, capable of dealing with both simulated and recorded data. A monitoring page was implemented to be able to perform daily checks on the data quality of the detection units and slow control parameters. A database was created to organize and store the incoming event files from the prototypes. An internal effort, called Data Challenge 2, encouraged all collaborators to develop, test and validate new reconstruction methods. For this, a realistic Monte Carlo simulation library with $200,000$ events was produced, containing raw-like ADC traces as well as the corresponding electric field traces. The antenna response and radio-frequency (RF) chain were also included, along with 22uV/m gaussian noise simulating the random (mostly Galactic) background. In addition, a 5 ns gaussian smeared "trigger" time, simulating the uncertainty in the time-stamping of triggers, and a Gaussian amplitude smearing of 7.5% were implemented.

This library of simulated events is used to test electric field reconstructions with a convolutional neural network, to perform directional reconstruction based on the polarization of the signal, to do trace de-noising using Machine Learning and for the reconstruction of inclined air showers. A plane wave front (PWF) model [13] is used for a rough directional reconstruction, calculated analytically with error estimation. A Lateral Distribution Function empiral fit is being tested with graph neural networks for extensive air shower studies. And lastly, simulation based inference for energy and direction reconstruction is being investigated. A description of the mentioned methods is given in [14]. Preliminary results obtained using GP300 and G@A data are shown in the following sections.

4.1 Reconstructed events

The plane wave front (PWF) [13] and the spherical wave front (SWF) [6] fits were applied independently on events in online coincidence from G@A, i.e., events with more than three self-triggered antennas in time coincidence. Note that the SWF requires at least five stations in time coincidence. The directional reconstructions had satisfactory preliminary results, pointing towards a nearby village, an expected source of man-made radio frequency interference (RFI) pulses. There

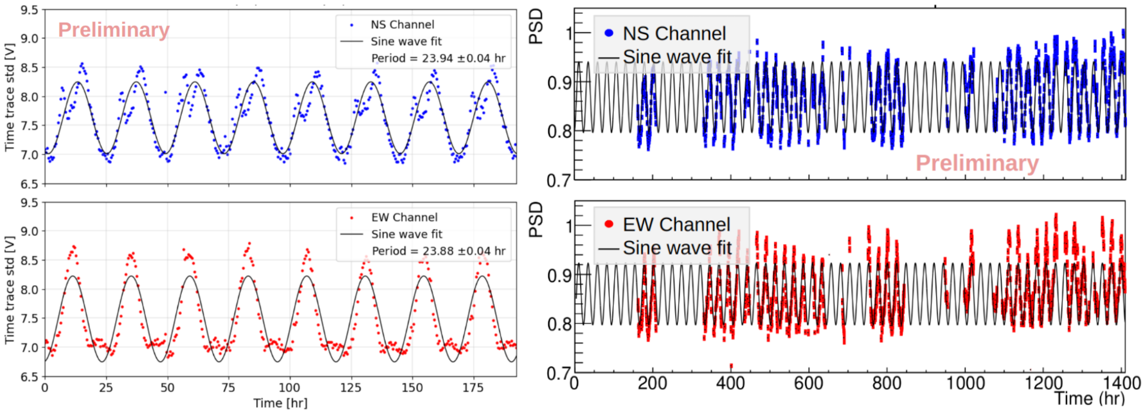

Figure 6: Amplitude variation for the periodic data of GP300, on the left, and of G@A, on the right. The period of oscillation of the straightforward sine wave fit matched the expected value for the galaxy background variation, a strong indication that the detectors are sensitive to the galactic emission at both sites.

were also events in close reconstructed position w.r.t. each other, an indication of plane tracks. The results are discussed more thoroughly in [11].

For the GP300 setup, a radio beacon was built near the DAQ computer for specific self-trigger runs. Data from this run were analyzed, using an offline coincidence search. The same PWF [13] and SWF [6] independent fits were performed. The preliminary results for the beacon position were also satisfactory, see Figure 5 on the left. A group of events had the position reconstruction west to the true beacon position. Investigation on maps revealed a local mine nearby to the reconstructed positions, see Figure 5 on the right. These results not only validated the directional reconstruction on GRAND events, but also demonstrated capability to deal with unexpected background sources.

4.2 Galactic background searches

The periodically triggered data are also used for galactic background searches. It is known that the galaxy emits electromagnetic radiation in the radio frequency range, mostly near its center and around the galactic plane. This emission creates a fluctuating background which has its amplitude modulated by an expected period of 23h56min or 23.934 hours. Thus, by inspecting the amplitude of the periodically triggered data, one expects to observe a modulation period equal to that of the galaxy, should the detection units be sensitive enough. This preliminary analysis was done using both GP300 and G@A data, where a sine wave fit indicated a period of oscillation close to the 23.934 hours, see Figure 6. These results are a strong indication that both prototypes are sensitive to the galactic background, however the analysis is still on-going. At a later stage, it is envisioned to use this emission for detector calibration.

5. Summary and Perspectives

The GRAND Collaboration is ready to move to the next stages of deployment. It was reported that three prototype arrays were deployed and went through the commissioning phase. The GRAND setup was verified and the first data is being collected. The Collaboration has put effort into developing the required software tools to handle and analyze the incoming events. A realistic

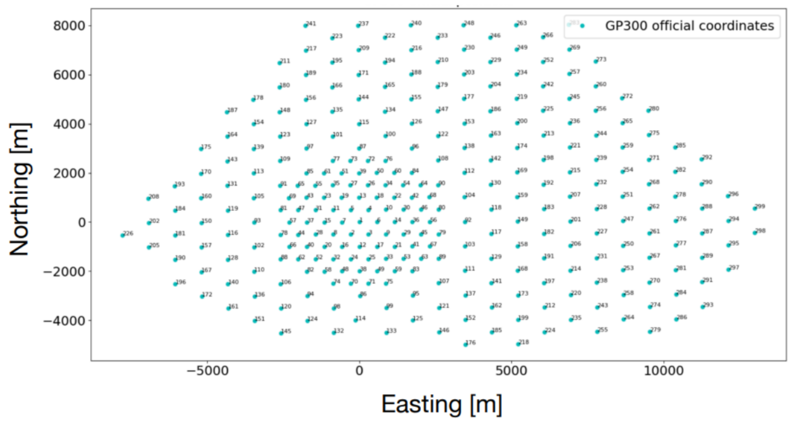

Figure 7: Approved positions for the complete GP300 antenna array, the final stage of the first GRAND prototype array.

Monte Carlo library was prepared and used to test the development of new air shower reconstruction methods. The data of both the G@A and GP300 prototypes are being analyzed with preliminary results indicating that the setup and reconstruction methods are well understood. At present, cosmic ray searches are on-going at both prototypes.

For the next stage of GP300, the positions for the final setup were approved, see Figure 7. In November 2024, The deployment of 70 more antennas at the GP300 site started, to be continued in March 2025 and followed by commissioning. When ready to take data by early 2026, the GP300 setup can be used to probe the galactic to extragalactic transition for cosmic rays and look for fast radio bursts (FRBs). The R&D for GRAND10k is on going as well, with a novel proposition for the next stage of GRAND in Argentina. The Hybrid Elevated Radio Observatory for Neutrinos (HERON) is a proposed hybrid array with GRAND-type standalone antennas and BEACON-type phased stations, to be deployed in the San Juan Province, Argentina. HERON would be a discovery instrument for UHE neutrinos and would work in synergy with the GP300 setup in China.

References

[1] GRAND Collaboration, *Science China Physics, Mechanics, and Astronomy* 63 (1) (2020) 219501.
[2] H. Falcke *et al.*, *Nature* 435 (2005) 313–316.
[3] LOFAR Collaboration, *AIP Conf. Proc.* 1535 (2013) 105–110.
[4] D. Ardouin *et al.*, *Nuclear Instruments and Methods in Physics Research Section A* 555 (2005) 148-163.
[5] S. de Jong, *PoS ICHEP2016* (2017) 080.
[6] D. Charrier, *et al*., *Astroparticle Physics* 110 (2019) 15 – 29.
[7] C. Guépin, K. Kotera, F. Oikonomou, *Nature Reviews Physics 4* (11) (2022) 697–712
[8] V. Decoene, *et al.*, *Astroparticle Physics* 145 (2023) 102779.
[9] K. Kotera, *PoS ARENA2024* (2024) 057.
[10] S. Chiche, *PoS ARENA2024* (2024) 059.
[11] B. de Errico, PoS UHECR2024 (2025) 076.
[12] GRAND Collaboration, *Computer Physics Communications* 308 (2025), 109461.
[13] A. Ferrière, *et al.* (2024). arXiv:2408.15677.
[14] O. Macias, *PoS ARENA2024* (2024) 062.
[15] Pierre Auger Collaboration, *Nuclear Instruments and Methods in Physics Research Section A*, 798 (2015) 0168-9002.