The KASCADE-Grande Experiment and the LOPES Project

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KASCADE-Grande is the extension of the multi-detector setup KASCADE to cover a primary cosmic ray energy range from 100 TeV to 1 EeV. The enlarged EAS experiment provides comprehensive observations of cosmic rays in the energy region around the knee. Grande is an array of 700 x 700 m^2 equipped with 37 plastic scintillator stations sensitive to measure energy deposits and arrival times of air shower particles. LOPES is a small radio antenna array to operate in conjunction with KASCADE-Grande in order to calibrate the radio emission from cosmic ray air showers. Status and capabilities of the KASCADE-Grande experiment and the LOPES project are presented.

1. Introduction

KASCADE-Grande allows a full coverage of the energy range around the so called "knee" of the primary cosmic ray spectrum (see Fig. 1). There are different theoretical attempts to explain the mystery of the origin of the "knee"

called change of the slope in the all-particle energy spectrum of cosmic rays. Either the knee energy is defined by the probability of an escape from the magnetic field of our Galaxy or by the limit of acceleration in supernova remnants or other galactic objects. Both classes of theories (diffusion or acceleration based) predict knee positions occurring at constant rigidity of the particles. On the other hand, the hypothesis of new hadronic interaction mechanisms at the

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knee energy, as for example the production of heavy particles in pp collisions, implies an atomic mass dependence of the knee positions. It is obvious that only detailed measurements and analysis of the primary energy spectra for the different incoming particle types can validate or disprove some of these models (see also [1]). From KASCADE [2] measurements we do know that at a few times 10^{15} eV the knee is due to light elements [3], that the knee positions depend on the kind of the incoming particle and that cosmic rays around the knee arrive our Earth isotropically [4,5]. KASCADE-Grande [6,7], measuring higher energies, will prove, if exists, the knee corresponding to heavy elements. Additionally KASCADE could show that no hadronic interaction model describes very well cosmic ray measurements in the energy range of the knee and above [8]. These model uncertainties are due to the lack of accelerator data at these energies and especially for the forward direction of collisions. Multi-detector systems like KASCADE and KASCADE-Grande offer the possibility of
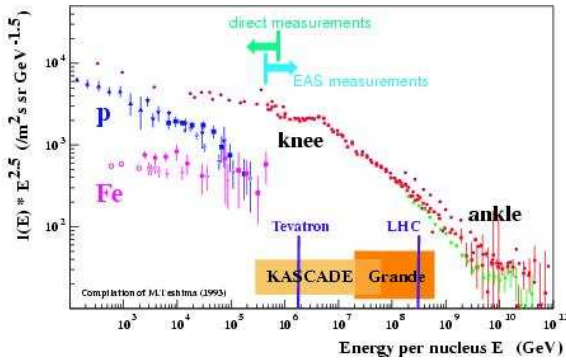

Figure 1. Primary cosmic ray flux and primary energy range covered by KASCADE-Grande.

testing and tuning the different hadronic interaction models. With its capabilities KASCADE-Grande is also the testbed for the development and calibration of new air-shower detection techniques like the measurement of EAS radio emission.

2. The KASCADE Experiment

The KASCADE experiment (Fig. 2) measures showers in a primary energy range from 100 TeV to 80 PeV and provides multi-parameter measurements on a large number of observables concerning electrons, muons at 4 energy thresholds, and hadrons. The main detector components of KASCADE are the Field Array, Central Detector and Muon Tracking Detector. The Field Array measures the electromagnetic and muonic components with 5 MeV and 230 MeV energy
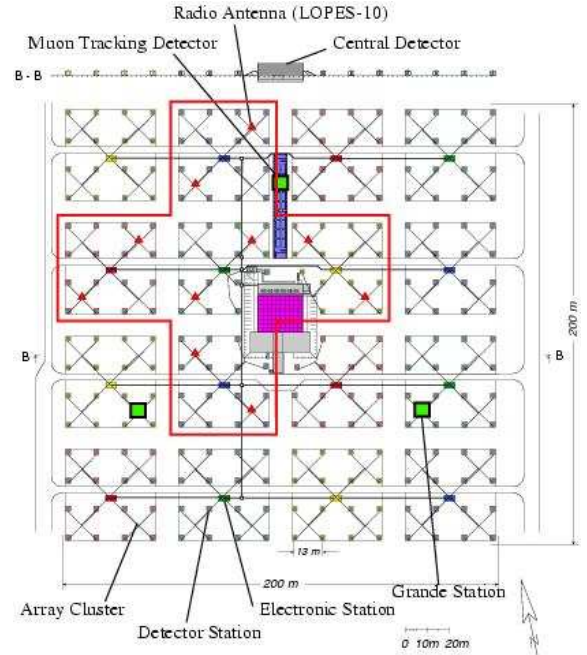

Figure 2. The main detector components of the KASCADE experiment: (the 16 clusters of) Field Array, Muon Tracking Detector and Central Detector. The location of 10 radio antennas is also displayed, as well as three stations of the Grande array.

threshold, respectively. It provides basic information about the arrival direction and core position as well as number of muons and electrons of the observed shower. The Muon Tracking Detector measures the angles-of-incidence of muons with 800 MeV energy threshold. The Central Detector consists mainly of a hadron sampling calorimeter;

three other components - trigger plane, MWPC, LST - offer additional valuable information on the penetrating muonic component at 490 MeV and 2.4 GeV energy thresholds. Main results of KASCADE are summarized in [1].

3. The KASCADE-Grande Experiment

The multi-detector concept of the KASCADE experiment has been translated to higher primary energies through KASCADE-Grande to solve the threefold problem: unknown primary energy, primary mass and characteristics of the hadronic interactions. This requires measurements on many shower parameters by using a multi-detector system to get redundant informations. Consistent experimental and simulated data are compared in order to estimate the mass and energy of the primary particles. Then multidimensional simulated distributions of observables can be compared with experimental ones in order to validate the interaction models.

3.1. The Grande Array

The 37 stations of the Grande Array (Fig. 3), located inside Karlsruhe Research Center, extend the cosmic ray measurements up to primary energies of 1 EeV. The Grande stations, 10 m^2 of plastic scintillator detectors each, are spaced at approximative 130 m covering a total area of ~ 0.5 km^2. There are 16 scintillator sheets in a station read-out by 16 high gain photomultipliers; 4 of the scintillators are read-out also by 4 low gain PMs. The covered dynamic range is up to 3000 mips/m^2. A trigger signal is build when 7 stations in a hexagon (trigger cluster, see Fig. 3) are fired. Therefore the Grande Array consists of 18 hexagons with a total trigger rate of 0.5 Hz.

3.2. The Piccolo Array

Additionally to the Grande Array a compact array, named Piccolo, has been build in order to provide a fast trigger to KASCADE ensuring joint measurements for showers with cores located far from the KASCADE array. The Piccolo array consists of 8 stations with 11 m^2 plastic scintillator each, distributed over an area of 360 m^2. One station contains 12 plastic scintillators organized in 6 modules; 3 modules form a so-called elec-
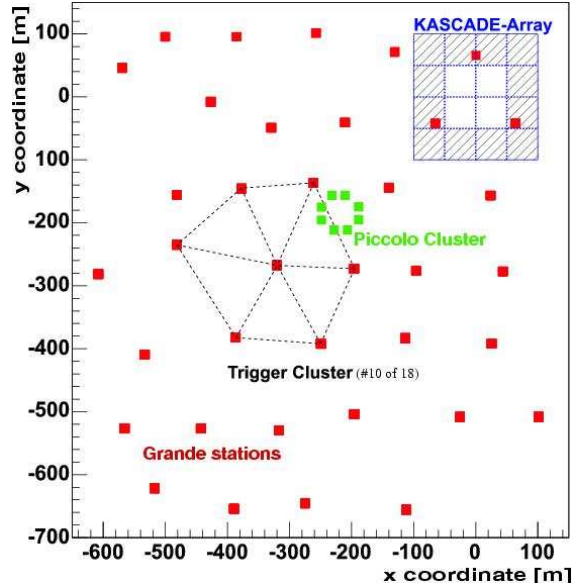

Figure 3. Sketch of the KASCADE-Grande experiment.

tronic station providing ADC and TDC signals. A Piccolo trigger is built and sent to KASCADE and Grande when at least 7 out of the 48 modules of Piccolo are fired. Such a logical condition leads to a trigger rate of 0.3 Hz.

4. Measurements at KASCADE-Grande

Fig. 4 shows, for a single event, the lateral distribution of electrons and muons reconstructed with KASCADE and the charge particle densities measured by the Grande stations. This example shows the capabilities of KASCADE-Grande and the high quality of the data. The KASCADE-Grande reconstruction procedure follows iterative steps: shower core position, angle-of-incidence and total number of charged particles are estimated from Grande Array data; the muon densities and with that the reconstruction of the total muon number is provided by KASCADE muon detectors; by subtracting it from the number of charged particles, the total electron number is estimated. The reconstruction accuracy of the shower core position and direction is in the order of 4 m (13 m) and 0.18° (0.32°) with 68% (95%) confidence level for simulated proton and
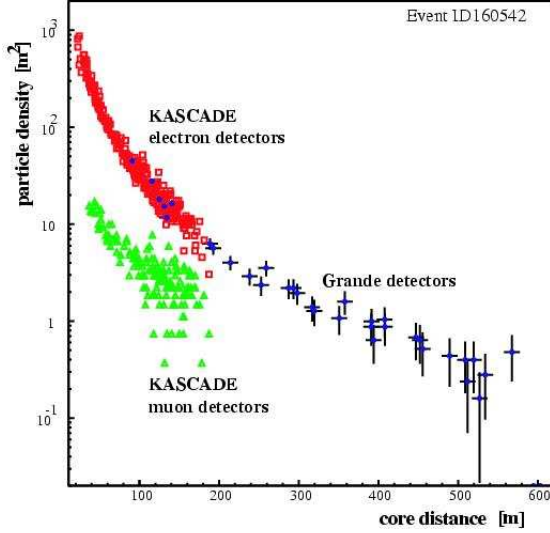
Figure 4. Particle densities in the different detector types of KASCADE-Grande measured for a single event.

iron showers at 100 PeV primary energy and 22° zenith angle [9]. The statistical uncertainty of the shower sizes are around 15% for both, the total numbers of electrons and muons. The critical point of the KASCADE-Grande reconstruction is the estimation of the muon number due to the limited sampling of the muon lateral distribution by the KASCADE muon detectors. The systematic uncertainty for the muon number depends on the radial range of the data measured by the KASCADE array and the chosen lateral distribution function [9]. In Fig. 5 the mean lateral distributions of charged particles for two zenith angle ranges and the shower core distribution for a 3-day test-run are presented. The data of this test-run are used to optimize the reconstruction procedures at KASCADE-Grande. Both distributions show reasonable results and are the basis for further reconstruction improvements.

At the KASCADE experiment, the two-dimensional distribution shower size - truncated number of muons played the fundamental role in reconstruction of energy spectra of single mass groups. For the same run time, due to its 10 times larger area compared with KASCADE, the Grande Array sees a significant number of showers at primary energies ∼10 times higher
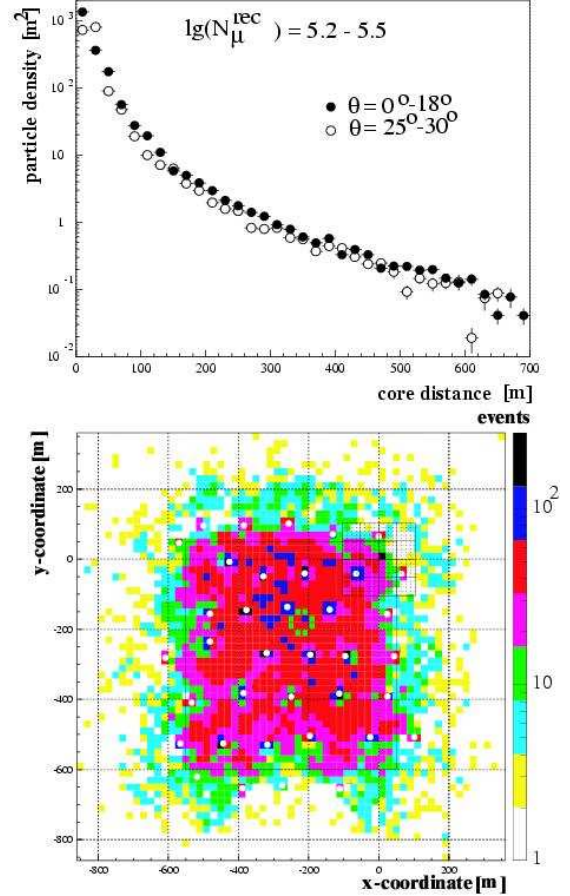

Figure 5. Mean lateral distributions of charged particles for two zenith angles ranges and distribution of the shower core positions reconstructed from Grande Array measurements at a 3-day test-run.

(Fig. 6). Hence fig. 6 shows the capability of KASCADE-Grande to perform an unfolding procedure like in KASCADE [1].

To improve further the data quality a self-triggering, dead-time free FADC-based DAQ system will be implemented in order to record the full time evolution of energy deposits in the Grande stations at an effective sampling rate of 250 MHz and high resolution of 12 bits in two gain ranges [10]. This will lead to an intrinsic electron-muon separation of the data signal at the Grande Array.
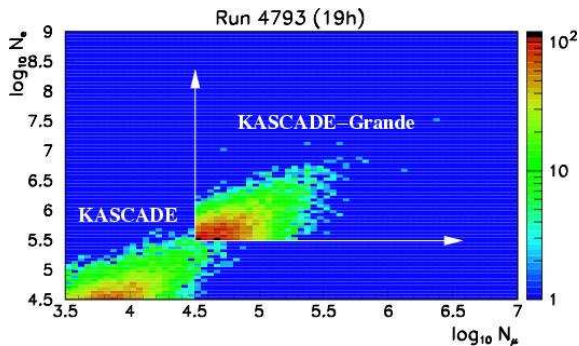
Figure 6. Comparison between KASCADE and KASCADE-Grande data for a combined test-run.

5. The LOPES Project

LOFAR (**LO**far **F**requency **AR**ray) will be a new digital interferometer and is an attempt to revitalize astrophysical research at 20-200 MHz with the means of modern technology [11]. The received waves from outer space will be digitized and sent to a central super-cluster of computers. LOFAR combines the advantages of a low gain antenna (large field of view) and high-gain antenna (high sensitivity and background suppression); these makes it a powerful tool also for studying radio emission in air-showers. A "**LO**far **P**rototyp**E S**tation" (LOPES) is under construction at the KASCADE-Grande location in order to test the LOFAR technology and demonstrate its capability for EAS measurements.

The interaction of the shower electrons and positrons with the Earth magnetic field leading to geosynchrotron emission is expected to be the dominant factor for radio emission at the cosmic ray air shower development [12]. Due to the low attenuation of radio waves, the emission is primarily a measure of the total electron and positron content in the shower maximum. The shower thickness is of order of the wavelength in the 100 MHz regime, thus coherence and interference effects are important at this frequency band. As a consequence, the shower geometry is imprinted in the measured wavefront of the radio antennas. Again, coherence of the wave front would lead to a quadratic increase of the radio pulse with primary particle energy [13]. For ultra-high energies radio detection is expected to have the most favorable

Figure 7. Dipole radio antenna in the Field Array of KASCADE. A Grande station on top of the Muon Tracking Detector is also seen.

signal-to-noise ratio compared to all other forms of secondary radiation [14]. Also, in contrast to optical methods, the technique allows round the clock observations, and as radio has low attenuation, will allow large detector volumes.

At present, LOPES operates 10 dipole radio antennas (see Fig. 7) in coincidence with KASCADE [15]. The antennas are positioned in 5 out of the 16 clusters of KASCADE, 2 of them per cluster (see Fig. 2). The radio data is collected when a trigger is received from the KASCADE array. The logical condition for trigger is at least 10 out of the 16 clusters to be fired. This translates to primary energies above 10^{16} eV; such showers are detected at a rate of 2 per minute. The antennas operate in the frequency range of 40-80 MHz. A preliminary analysis of the first data has already been performed [16]. Fig. 8 shows a particularly bright event as an example. A crucial element of the detection method is the digital beamforming which allows to place a narrow antenna beam in the direction of the cosmic ray event. This is possible because the phase information of the radio waves is preserved by the digital receiver and the cosmic ray produces a coherent pulse. This method is also very effective in suppressing interference from the particle detectors which all radiate incoherently.

In the near future, 30 antennas will be installed at KASCADE-Grande. The FADC system planned for the Grande stations may play a key role in deconvoluting and subtracting the
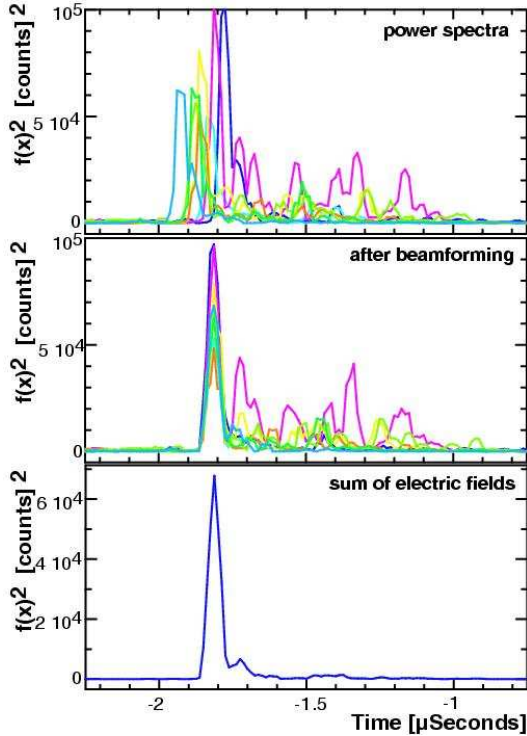
Figure 8. Steps of the reconstruction of a strong air shower event [16] detected by LOPES. In the upper part the received powers (squares of the electric fields) of 8 antennas before beamforming are overlayed. Powers after time shifting using the KASCADE shower direction information are displayed in the second panel. A clear signal is proved by displaying the power after beamforming of the electric field (lower part).

radio signals produced by the particle detectors. With an amount of 1000 measured events above 10^{17} eV, KASCADE-Grande will be able to calibrate the radio emission in extensive air showers with high accuracy.

6. Conclusions

The extension of KASCADE to the KASCADE-Grande experiment, accessing higher primary energies, will prove the existence of a knee-like structure corresponding to heavy elements. KASCADE-Grande will keep the multi-detector concept for tuning different interaction models

at primary energies up to 10^{18} eV. There are promising perspectives for detecting radio emission in extensive air showers with the LOPES set up and to perform a calibration of the radio pulses. This can lead to a possible new detection tool for future experiments.

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