Nuclear Instruments and Methods in Physics Research A 639 (2011) 42–45

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A new 1 km^2 EAS Cherenkov array in the Tunka Valley

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ARTICLE INFO

Available online 21 October 2010

Keywords:
Primary cosmic rays
Extensive air showers
Cherenkov light
Energy spectrum
Photodetector

ABSTRACT

A new 1 km^2 EAS Cherenkov detector in the Tunka Valley has been put into full operation in the fall of 2009. In this paper we give a short description of the detector and discuss its physics capabilities.

1. Introduction

Despite the fact that cosmic rays were discovered almost one hundred years ago it is still quite unclear how and where they are originated and accelerated to such a giant energies of 10^{20} eV and even higher. Hence shedding light on cosmic rays origin and acceleration mechanisms is among the most important and intriguing problems of contemporary astroparticle physics.

The energy spectrum of primary cosmic rays follows a power law over a very wide energy region. In the high energy domain the spectrum has several remarkable features: the "knee" at $\sim 3\times 10^{15}$ eV; a possible second "knee" at $\sim(2–5)\times 10^{17}$ eV; the "ankle" at $\sim 3\times 10^{18}$ eV and at last the famous, so called, GZK cutoff at $\sim(3–5)\times 10^{19}$ eV.

The TUNKA experiment is located in the famous Tunka Valley in Buryatia, Siberia, about 50 km from the south edge of the lake Baikal at an altitude of 675 m above the sea level (Fig. 1) and detects the EAS Cherenkov light exploiting Earth's atmosphere as a calorimeter.

The history of the TUNKA EAS Cherenkov experiment spans nearly two decades. The experiment started in the early 1990s with a small detector TUNKA-4 [1,2] based on four hemispherical QUASAR-370G [3] hybrid phototubes and evolved in the early 2000s to TUNKA-25 array [4,5] with 25 QUASAR-370G phototubes. The experiment at those stages studied primary cosmic rays in the energy region of 10^{15}–10^{17} covering the knee. In Fig. 2 one can see the TUNKA-25 results along with data from other experiments [6]. There is an obvious lack of experimental data in the energy range of 10^{16}–10^{18} eV although it is widely accepted that the transition from Galactic to extragalactic cosmic rays occurs there. Unfortunately a relatively small sensitive area of the TUNKA-25 did not allow the array to be used in studies of cosmic rays in this energy range. For these purposes it was decided to deploy a new EAS Cherenkov detector with 1 km^2 geometric area.

2. TUNKA-133 detector

The main goal of the new array, christened TUNKA-133 [7,8], is to measure primary cosmic rays energy spectrum and mass composition in the energy range of 10^{15}–10^{18} eV. The TUNKA-133 detector consists of 133 optical modules based on 8″ Thorn-EMI9350KB PMTs. The detector covers the 1 km^2 area. All optical modules

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doi:10.1016/j.nima.2010.09.142

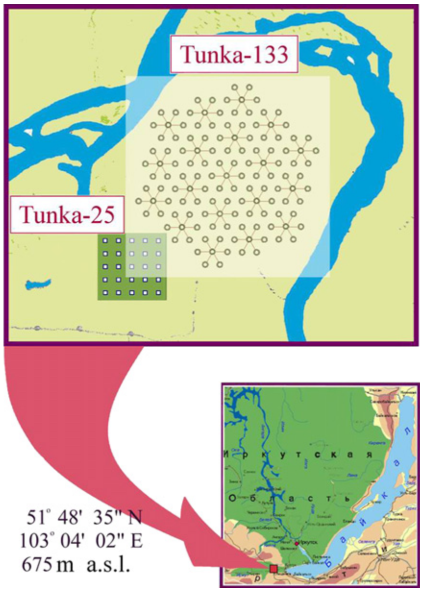

Fig. 1. Site of the TUNKA experiment.

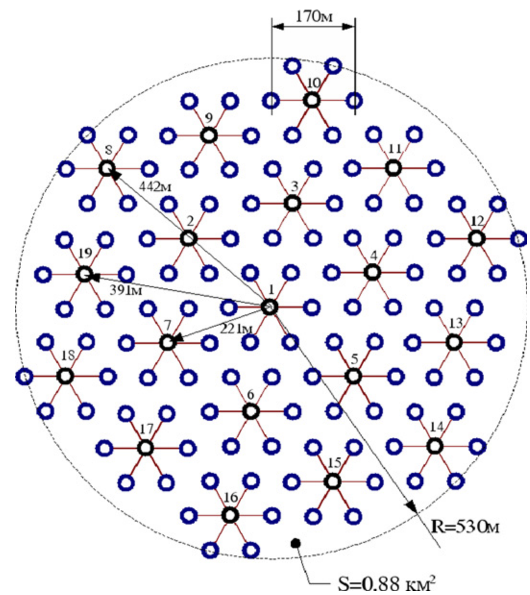

Fig. 3. Schematic layout of the TUNKA-133 EAS Cherenkov detector.

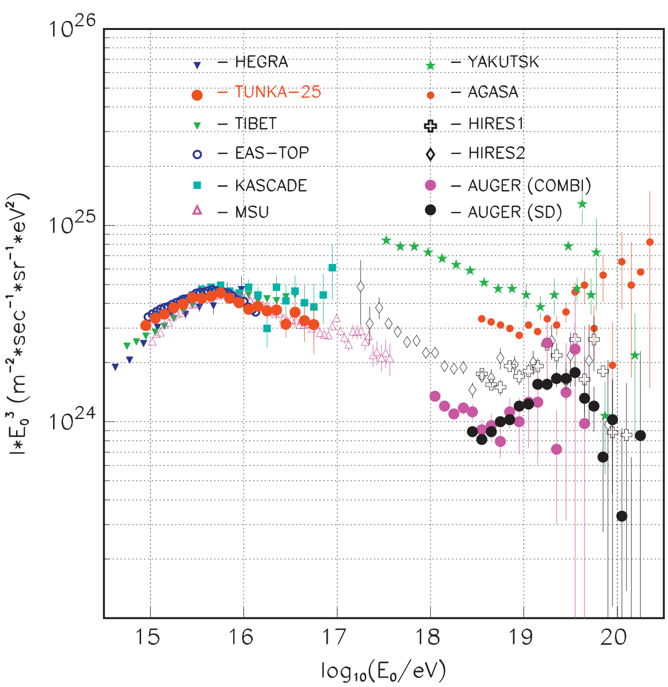

Fig. 2. Primary cosmic ray energy spectrum.

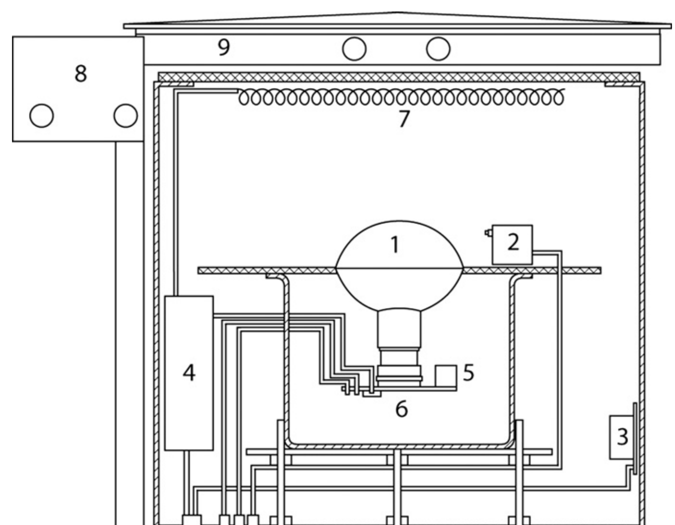

Fig. 4. Schematic drawing of the optical module: (1) PMT Thorn-EMI9350KB, (2) LED driver, (3) temperature controller, (4) DC–DC converter and heater driver. (5) preamplifier, (6) active voltage divider, (7) heater of acrylic cover, (8) lid driver and (9) lid.

are grouped into 19 clusters, each composed of seven modules—six hexagonally arranged and one in the centre of the cluster, as shown in Fig. 3. The distance between modules is 85 m. The detection efficiency of the optical module decreases smoothly to ~80% of that of the vertical efficiency at zenith angle of 40° and to 50% at 50°.

Each cluster is equipped with an electronic module fixed near cluster's central optical module. The optical module output signals are transferred to the electronic module by coaxial cables. In turn each electronic module is connected with the central DAQ system by a cable incorporating four optical fibres and four electrical cables.

The schematic drawing of the array optical module is shown in Fig. 4. The PMT, voltage divider, power supply (DC–DC converters) and preamplifier are fixed in a metal container with a thin acrylic sheet provided with heater to prevent dew, frost and condensate. To have high dynamic range ($\sim 10^4$) anode and dynode signals of the PMT are used and they are transferred to the cluster's electronic module via two R-58 coaxial cables, each 95 m long. A fast LED driver [9] based on ultra-bright blue LED is attached to the PMT's photocathode for calibration purposes. The optical module has remote controlled lid to avoid the PMT illumination during day time and to protect from rain and snow. The optical module is run by a controller, which is connected with cluster's electronic module via twisted pair by RS-485 protocol. The optical modules are designed to withstand ambient temperature ranging from -40 to +20 °C.

The array DAQ system [10] is arranged in hierarchical way (Fig. 5) from the cluster electronic module to the central DAQ station. The cluster electronics includes the cluster controller, four four-channel FADC boards, an adapter unit for connection with

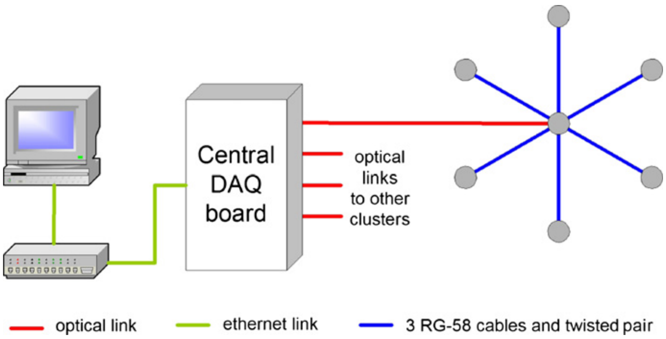

Fig. 5. Conceptual scheme of the array data acquisition system.

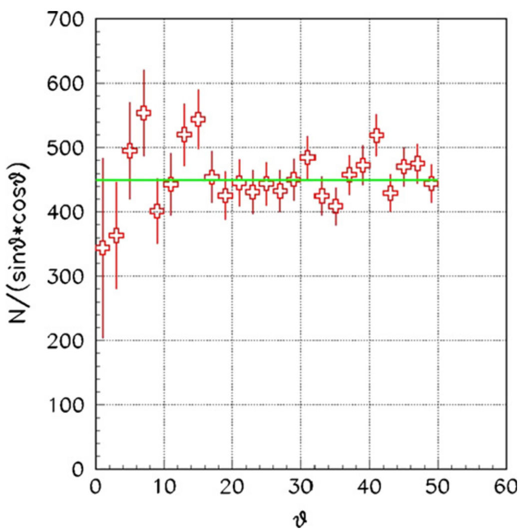

Fig. 6. Zenith angle angular distribution of events detected by TUNKA-133.

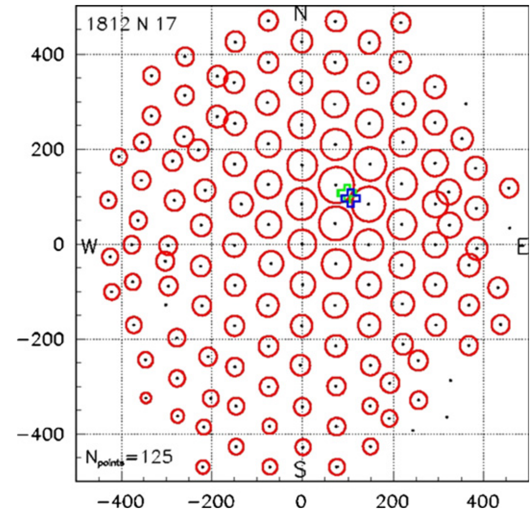

Fig. 7. High energy event detected by TUNKA-133. Dots—optical modules, red circles depict signals amplitudes, black and grey crosses are the shower core positions defined by LDF and WDF methods, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

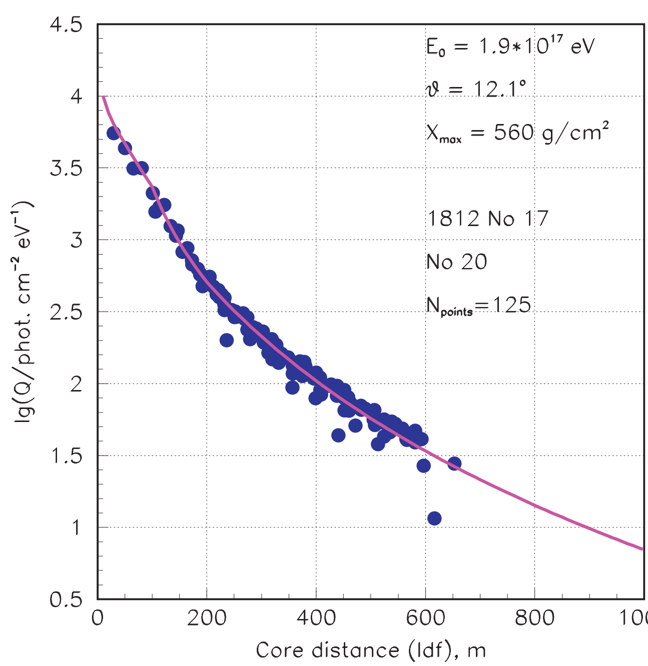

Fig. 8. Lateral distribution of EAS Cherenkov photons flux (LFD) for the event depicted in Fig. 7. Dots are Cherenkov photons density detected by individual optical modules of the array. Line is a fitting curve.

optical modules and a special temperature controller. The 12 bit and 200 MHz sampling FADC boards are based on AD9430 fast ADCs and FPGA XILINX Spartan XC3S200 microchips. Anode and dynode signals of all cluster's PMTs are digitized by FADCs and transferred to the central DAQ by an optical transceiver. The temperature controller is connected with the central DAQ by radio channel via XBee-PRO module.

Signals from at least three optical modules of one cluster in a time window of 500 ns serve as the cluster trigger. The arrival time of local trigger is latched by the cluster clock.

The central DAQ station consists of five DAQ boards strongly synchronized by a single 100 MHz oscillator. The boards are connected to the master PC by 100 MHz Ethernet line.

The array allows the reconstruction of primary energy with 15% and EAS maximum depth 25 g/cm^2 accuracies. The energy threshold is close to 1 PeV.

3. First results and outlook

The TUNKA-133 EAS Cherenkov detector has been put into full operation in October 2009. The zenith angle distribution of events with primary energy $E > 7 \times 10^{15}$ eV detected by the array and corrected by the angular dependence of the detection efficiency of the array optical modules is presented in Fig. 6. It is seen from this figure that the detector has uniform angular response to primary cosmic rays up to zenith angle of 50°.

An example of event detected by TUNKA-133 is shown in Fig. 7. In the event 125 optical modules were fired. Here black dots are optical modules and red circles depict logarithm of signal amplitudes registered by corresponding module. The reconstructed primary energy and zenith angle of this event are 2.0×10^{17} eV and 12.6°, respectively.

Black and grey crosses are the shower core positions defined by the "LDF" and "WDF" methods, respectively. In the first method the shower core position is determined by fitting the Cherenkov photon flux density registered by individual optical modules with the lateral distribution function (LDF) (Fig. 8) characterized by two variable parameters—steepness (P) of LFD and Cherenkov photon flux density (Q_{175}) at the distance of 175 m from the shower core [11]. The parameter Q_{175} is a measure of shower energy. The parameter P is used to determine the depth of shower maximum X_{max}.

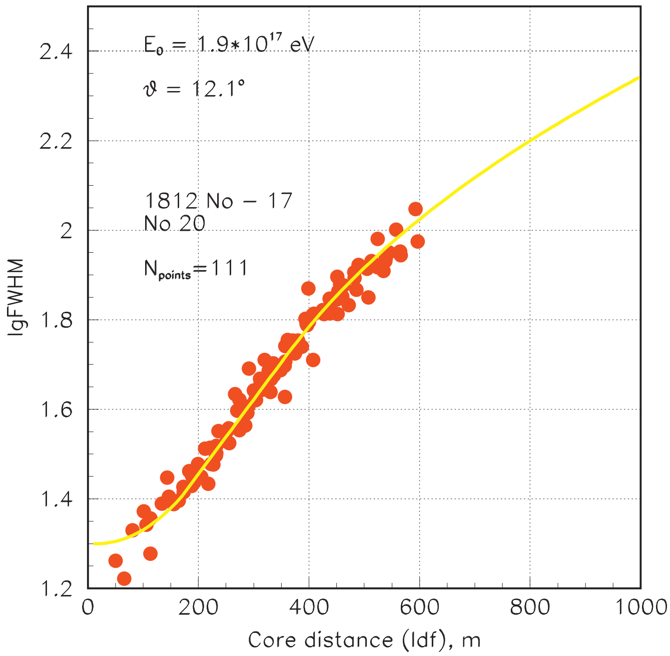

Fig. 9. Width–distance function of EAS Cherenkov pulses (WDF) for the event depicted in Fig. 7. Dots are pulse width (FWHM) in nanoseconds detected by individual optical modules of the array. Line is a fitting curve.

The second method (WDF) is based on the use of EAS Cherenkov signal width (FWHM) [12]. The signal widths detected by the optical modules of the array are fit by a width–distance function (WFD) with only one variable parameter $\tau(4\,0\,0)$ which is the signal width at 400 m from the shower core. The parameter is used to determine $X_{\max}$. Fig. 9 illustrates the use of the WDF method.

In the upcoming two years (2011–2012) it is planned to make the array more complex adding 20 muon detectors and a net of radio antennas. The muon detectors are plastic scintillator counters 10 m^2 meters area each put underground. The detection of muon component of EAS will help in the mass composition measurements and in the array cross calibration as well. The detection of showers radio pulses will increase the array sensitivity for ultra-high energy cosmic rays ($\geq 10^{18}$ eV).

It is also planned to install six additional clusters around the TUNKA-133 at ~1 km distance from the centre of the array. It will increase the effective area of the array at 10^{17} eV by a factor of 4.

4. Conclusion

The new TUNKA-133 EAS Cherenkov detector with 1 km^2 geometric area has started taking data since the fall of 2009. The array is capable to study primary cosmic rays energy spectrum and mass composition in a wide energy range of 10^{15}–10^{18} eV from the "knee" to "ankle" with a good precision. The TUNKA-133 detector has capabilities to give new experimental data to improve our understanding of origin and acceleration mechanisms of high and ultra-high energy cosmic rays.

Acknowledgements

The present work is supported by the Russian Ministry of Education and Science, program "Development of Scientific Potential of High Energy Schools" (projects 2.2.1.1/1483, 2.1.1/1539, 2.2.1/5901) and the Russian Foundation of Basic Research (Grants 09-02-1000, 09-02-12287-ofi_m and 10-02-00222). The authors are indebted very much to Dr.V.Ch. Lubsandorzhieva for careful reading of the article and many useful discussions.

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