Tunka-133: preliminary results from the first year of operation

B.V. Antokhanov^a, S.F. Berezhnev^a, D. Besson^b, N.M. Budnev^c, A. Chiavassa^d, O.A. Chvalaiev^c, O.A. Gress^c, A.N. Dyachok^c, N.I. Karpov^a, N.N. Kalmykov^a, A.V. Korobchenko^c, V.A. Kozhin^a, E.E. Korosteleva^a, L.A. Kuzmichev^a, B.K. Lubsandorzhiiev^e, R.R. Mirgazov^c, M.I. Panasyuk^a, L.V. Pankov^c, E.G. Popova^a, Vasili V. Prosin^{a,*}, V.S. Ptuskin^f, Yu.A. Semenev^c, B.A. Shaibonov (junior)^e, A.A. Silaev^a, A.A. Silaev (junior)^a, A.V. Skurikhin^a, J. Snyder^b, C. Spiering^g, M. Stockham^b, R. Wischnewski^g, I.V. Yashin^a, A.V. Zablotzky^a, A.V. Zagorodnikov^c

^aSkobeltsyn Institute of Nuclear Physics, Moscow State University, Russia

^bDept. of Physics and Astronomy, University of Kansas, USA

^cInstitute of Applied Physics, Irkutsk State University, Irkutsk, Russia

^dDipartimento di Fisica Generale dell'Università' and INFN, Torino, Italy

^eInstitute of Nuclear Research, Russian Academy of Sciences, Moscow, Russia

^fInstitute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Moscow, Russia

^gDESY, Zeuthen, Germany

The new array Tunka-133 started data taking at the end of 2009. The apparatus records the Cherenkov light pulse waveform of extensive air showers (EAS). It consists of 133 optical detectors deployed over an area of about 1 km². About two million events have been collected during 286 hours of clean moonless nights in winter 2009-2010. Using these data, we present methods of primary cosmic particle parameter reconstruction for EAS with the core both inside and outside the array and give preliminary results.

1. Introduction

The study of primary energy spectrum and mass composition in the energy range 10¹⁵ – 10¹⁸ eV is of crucial importance for the understanding of the origin of cosmic rays and of their propagation in the Galaxy.

The change from light to heavier composition with growing energy marks the energy limit of cosmic ray acceleration in galactic sources (SN remnants), and of the galactic containment. This effect was described by theory simulations ([1], [2], [3]) and confirmed by several experiments

(i.e.[4], [5], [6]). An opposite change from heavy to light composition at higher energy would testify the transition from galactic to extragalactic sources. An experimental evidence of such a behavior of the composition was reported in [7], [8].

To measure the primary cosmic ray energy spectrum and mass composition in the above mentioned intermediate energy range the new array Tunka-133 ([9], [11]), with nearly 1 km² internal area has been deployed in the Tunka Valley, Siberia. It records EAS Cherenkov light using the atmosphere of the Earth as a huge calorimeter and has much better energy resolution (~ 15%) than EAS arrays detecting only charged particles.

From 1994 to 2005, a series of experiments for the study of EAS with Cerenkov light has been performed in the Tunka Valley. The last one,

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Tunka-25 ([12]), operated from 2000 to 2005.

The sensitive area of Tunka-133 is ten times larger than that of its predecessor Tunka-25, and the solid angle is about 3 times bigger. Thus, the number of high energy events ($\geq 10^{16}$ eV) collected by Tunka-133 during one single January night was close to the number of such events collected by Tunka-25 during the whole winter season (~ 300 h).

The new array has collected data for about 286 h during clean moonless nights in winter 2009–2010.

2. Tunka-133 description

The Tunka-133 array consists of 133 optical detectors on the basis of PMT EMI 9350 with a hemispherical photocathode of 20 cm diameter. The detectors are grouped into 19 clusters each with seven detectors – six hexagonally arranged detectors and one in the center. The distance between the detectors in the cluster is 85 m (see Fig. 1).

Figure 1. Layout of the Tunka-133 array.

An optical detector consists of a 50 cm diameter metallic cylinder, containing a PMT. The container window is directed to zenith and covered with plexiglass heated against hoar-frost and dew. The detector is equipped with a remotely controlled lid protecting the PMT from sunlight and precipitation.

The detector efficiency vs. the zenith angle is shown in Fig. 2. This curve reflects the influence of the window edge as well as the atmosphere absorption due to Rayleigh and aerosols scattering of the Cherenkov light. The measured light flux was divided by this function to get the correct radiated flux proportional to the primary energy.

Figure 2. Acceptance of the optical detector vs. zenith angle.

The Cherenkov light pulses are sent via 100 m coaxial cable RG58 to the center of each cluster and digitized. The minimum pulse FWHM is about 20 ns. The dynamic range of the amplitude measurement is about $3 \cdot 10^4$. This is achieved by means of two channels for each detector extracting the signals from the anode and from an

intermediate dynode of the PMT with different additional amplification factors.

The data of all clusters is collected by the central DAQ and transferred via fiber-optics cables.

The Tunka-133 array has been deployed during 3 years since 2006 till 2009. The construction, data acquisition system and the on-line programs were corrected during all this time. The deployment operations were carried out during summer and autumn, and the test data acquisition was run during winter time. The first cluster operated during the winter 2006-2007, four clusters were in operation in 2007-2008, twelve clusters operated in 2008-2009. The total array of 19 clusters operated during the last winter 2009-2010.

3. Data processing

The processing of data from the new array differs from that of the previous array Tunka-25. The differences are related to the substantially larger area as well as to the pulse waveform recorded now by each detector. A detailed description of the total processing procedure was presented in [14].

The primary data record for each Cherenkov light detector contains 1024 amplitude values in steps of 5 ns. Thus, the waveform of every pulse is recorded, together with the preceding noise, as a total trace of 5 μ s duration. To derive the three main parameters of the pulse: front delay at a level 0.25 of the maximum amplitude (t_i), pulse area (Q_i) and full width at half-maximum FWHM $_i$, the method of pulse fitting with a smooth curve is used. The waveform of an EAS Cherenkov light pulse is rather complicated and can't be fitted with a simple function as e.g. a Gauss or gamma function. Therefore, a function was constructed which separately approximates front and tail of the pulse [14].

The relative delay of each cluster timer is measured at the start of the DAQ program. The difference of cluster delays is due to length differences of the fiber-optic connections. It is measured with an accuracy of 10 ns.

The pulse delay inside a cluster is caused by the delay in the connecting 100 m cable RG-58, PMT and pre-amplifier. Precise correction of the

in-cluster apparatus delay is made separately for each cluster by analysis of the residual time deflection of a pulse front at each detector from the reconstructed front of the shower. The standard deviation of the detector residual deflection distribution characterizes the accuracy of the pulse front reconstruction. The typical distribution of deflections for one of the detectors is shown in Fig. 3. The typical accuracy is about 2 ns.

Figure 3. The distribution of residual times for one detector.

The relative amplitude calibration is derived from the comparison of integral spectra of pulse charges Q_i for each detector. The procedure is the same as described in [12]. The absolute energy calibration is made as in [12] too.

4. Reconstruction of EAS parameters

The reconstruction of the EAS core position is performed with two methods - one by fitting of measured charges Q_i with the lateral distribution function (LDF) and one by a new method of

fitting the measured pulse widths by the width-distance function (WDF).

The EAS core is reconstructed with better accuracy the higher the value of the fitting function derivative is. The detailed study of LDF obtained from CORSIKA simulations [13] has shown that the derivative $dlgQ/dR$ fluctuates very much from event to event in the distance range from 0 to 100 m but has almost stable negative value in the range 100–200 m. This is the reason why the EAS Cherenkov light array has to have a radius of at least 150 m. The LDF shape is described by an expression with a single parameter, the steepness P [13]. P is strictly connected with the distance from the array to the EAS maximum [10]. This connection is used for measuring the shower maximum depth X_{max} .

The shape of the WDF is also obtained from CORSIKA simulations. We used 270 events simulated for both primary protons and iron nuclei, with energies from 10 to 30 PeV and zenith angles from 0° to 45° . Details of the simulation are presented in [14].

Taking into account the apparatus distortion of pulses in the PMT, pre-amplifier and the connecting coaxial cable, the pulse shape can be presented with the following expression:

$$\tau(R) = \begin{cases} \tau_{ch} \cdot \exp(b_1 \cdot (R - R_{ch})) & \text{for } R \leq R_{ch} \\ (\tau_{ch} + 200) \cdot \exp(b_2 \cdot (R - R_{ch})) - 200, & \text{for } R \geq R_{ch} \end{cases}$$

Here $\tau(R) = \text{FWHM}(R)$ in ns, R and R_{ch} in m. All the variables can be expressed via the FWHM at the core distance 400 m (τ_{400}):

$$\begin{aligned} b_1 &= 0.0045 \cdot \lg \tau_{400} - 0.00183 \\ b_2 &= 0.00088 \cdot \lg \tau_{400} - 0.000335 \\ R_{ch} &= 3976 - 3429 \cdot \lg \tau_{400} + 786 \cdot (\lg \tau_{400})^2 \\ \tau_{ch} &= \tau_{400} \cdot \exp(b_1 \cdot (R_{ch} - 400)), R_{ch} > 400 \\ \tau_{ch} &= (\tau_{400} + 200) \cdot \exp(b_2 \cdot (R_{ch} - 400)) - 200, \\ &\quad R_{ch} \leq 400 \end{aligned}$$

This function can be applied for the EAS core reconstruction for larger distances than the LDF because its derivative has a sufficiently big value at $R > 200$ m. We hope to use it for EAS with energies beyond 10^{17} eV and core distances up to 1–1.5 km. We expect that using the WDF will

Figure 4. Thickness of matter between the array and the EAS maximum vs. $\text{FWHM}(400)$.

allow to reconstruct the core position even outside the geometrical area of the array.

Figure 4 presents the connection between τ_{400} and the thickness of the atmosphere between the detector and the EAS maximum $\Delta X_{max} = X_0/\cos\theta - X_{max}$. Here $X_0 = 945 \text{ g cm}^{-2}$ is the vertical thickness of the atmosphere at the Tunka-133 site. This plot contains all the 270 MC events mentioned above. One can see that the points for different zenith angles and different nucleus mass occupy the same line with relatively small deflections: $\Delta X_{max} = 3400 - 1667 \cdot \lg \tau_{400}$.

Recording of the pulse waveform for each detector provides a more reliable approach to measure the EAS maximum depth X_{max} , since it allows to use different methods (LDF steepness and pulse width at 400 m $\tau(400)$) simultaneously.

5. Preliminary results

During the first winter (286 hours of clean weather during moonless nights) $\sim 2 \cdot 10^6$ events with $E > 10^{15}$ eV have been collected, among them about 20000 events with $E_0 > 10^{16}$ eV, about 200 events with $E_0 > 10^{17}$ eV and the core position inside the array and zenith angle

Figure 5. An example of an event detected by TUNKA-133. The radii of the circles are proportional to the logarithm of the Cherenkov light flux. $E = 3.9 \cdot 10^{17}$ eV, $X_{max} = 605$ g cm $^{-2}$. Core positions: $\star$ (reconstructed by using LDF), $\bigcirc$ (reconstructed by using WDF).

smaller than 45° . An example of a real event, registered with Tunka-133 is shown in Figs. 5,6,7. It is seen that experimental data are fitted rather good with the chosen functions LDF and WDF.

To check the simulated efficiency we analyse the zenith angle distribution of the recorded EAS with energy more than a fixed value. The resulting zenith angle distribution of EAS with energies larger than 15 PeV is presented in Fig.8. The new detector allows analyzing events with zenith angles up to 40° – 50° .

The preliminary energy spectrum and mass composition derived from these data will be presented in 2011.

6. Conclusion and Outlook

The short-term plan for data analysis is as follows:

Figure 6. Lateral distribution resulting from fitting the measured light fluxes (points) with the expression (1) (curve) for the event from fig. 6.

1. Reconstruction of the cosmic ray differential energy spectrum in the energy range $3 \cdot 10^{15} - 10^{18}$ eV.
2. Obtaining of experimental X_{max} distributions in narrow lgE_0 bins.
3. Simulation of X_{max} distributions for different primary mass groups.
4. Comparison of the experimental and combined simulated distributions and thus estimation of the most probable primary composition for every energy bin.

The use of the WDF will allow us reconstructing the EAS parameters of events far from the detectors and even with core positions outside the geometric area of the array. In this case, X_{max} will be measured with $\tau(400)$, and the primary energy will be reconstructed with the density of Cherenkov light flux at a core distance 400 m Q_{400} . To improve the accuracy of the core reconstruction for such events, we plan to install six new clusters on a circle of 1 km radius around the center of Tunka-133 array. The 42 additional op-

Figure 7. Dependence of Cherenkov light pulse width on the core distance for the event from fig. 6. Points – experiment, line – WDF.

Figure 8. Zenith angle distribution of events with energy $> 1.5 \cdot 10^{16}$ eV

tical detectors will enlarge the effective area by a factor 4 for energies larger than 10^{17} eV. The first distant cluster was installed in September 2010, the other five clusters will be installed in summer 2011.

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