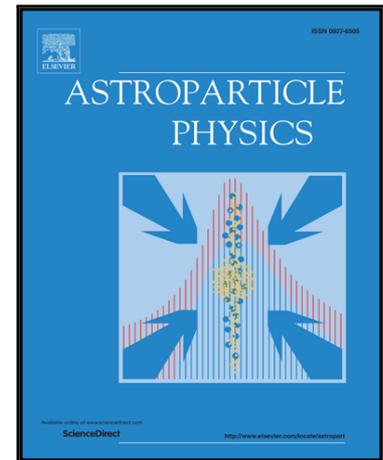


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# The primary cosmic-ray energy spectrum measured with the Tunka-133 array

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## Abstract

The EAS Cherenkov light array Tunka-133, with  $\sim 3 \text{ km}^2$  geometric area, is taking data since 2009. The array permits a detailed study of energy spectrum and mass composition of cosmic rays in the energy range from  $6 \cdot 10^{15}$  to  $10^{18}$  eV. We describe the methods of time and amplitude calibration of the array and the methods of EAS parameters reconstruction. We present the all-particle energy spectrum, based on 7 seasons of operation.

*Key words:* High energy cosmic rays; air shower; Cherenkov radiation; energy spectrum

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## 1 Introduction

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The study of energy spectrum and mass composition of primary cos-

mic rays in the energy range of  $10^{15}$  -  $10^{18}$  eV is of crucial importance for understanding origin and propagation of cosmic rays (CR) in the Galaxy. An increasing dominance of heavy nuclei from the "knee" up to  $10^{17}$  eV indicates the energy limit of CR acceleration in the standard model of particle acceleration in supernova remnants, see review [1]. At higher energies, the composition becomes lighter again up to  $2 \cdot 10^{18}$  eV. This may indicate a transition to an extragalactic origin of CR or the dominance of new Galactic sources of unknown nature, see [2] for discussion.

To measure the primary energy spectrum and mass composition of cosmic rays in the energy range mentioned above, the Tunka-133 array [3,4] with nearly  $3 \text{ km}^2$  geometrical area has been deployed in the Tunka Valley, Siberia. It records the Cherenkov light from Extensive Air Showers (EAS) using the Earth atmosphere as a huge calorimeter.

## 2 The Tunka-133 Array

The Tunka-133 array is located at an altitude of 670 m a.s.l. It consists of 175 optical detectors. The detectors are grouped into 25 clusters with seven detectors each – six hexagonally arranged detectors and one in the center. The distance between the detectors in a cluster is 85 m (see Fig. 1). 19 of the clusters are arranged as a dense central part of the array with a radius of about 500 m. These  $19 \times 7 = 133$  stations

gave the array its name. The remaining clusters are installed at distances of  $\approx 1 \text{ km}$  around the central part.

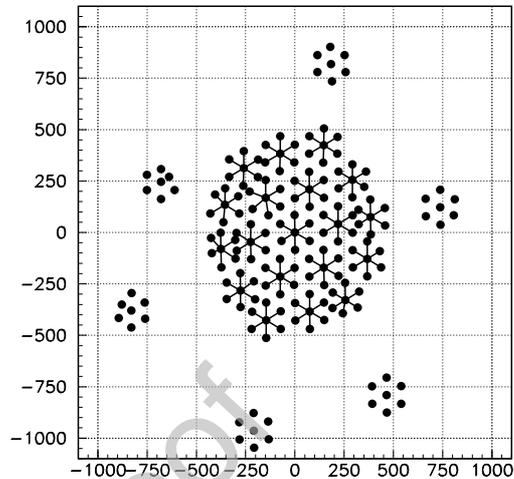


Fig. 1. Layout of the Tunka-133 array.

Each optical detector consists of a metallic cylinder with 50 cm diameter, containing a single PMT with a hemispherical photocathode of 20 cm. The container window consists of plexiglass and points vertically upward. It is heated against hoar-frost and dew. The detector is equipped with a remotely controlled lid protecting the PMT from daylight and precipitation.

Figure 2 shows the detector acceptance as a function of the zenith angle. The curve reflects the influence of the window edge as well as the atmosphere absorption due to Rayleigh and aerosol scattering of the Cherenkov light. To check the simulated detector acceptance we analyse the zenith angle distribution of the recorded EAS with reconstructed energies larger than 10.0 PeV. The resulting zenith angle distribution is

shown in Fig. 3. The distribution is flat up to  $50^\circ$ .

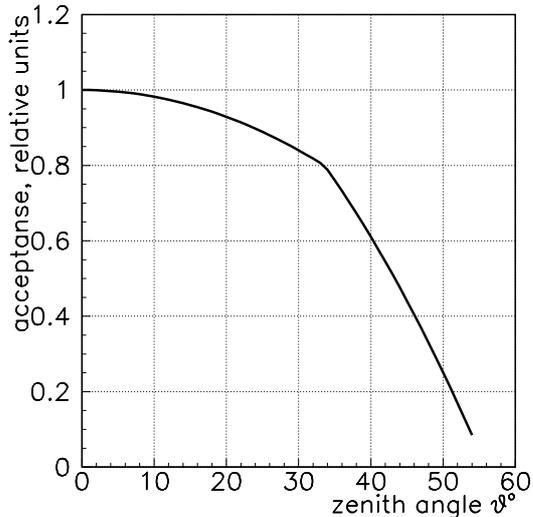


Fig. 2. Acceptance of the optical detector vs. zenith angle.

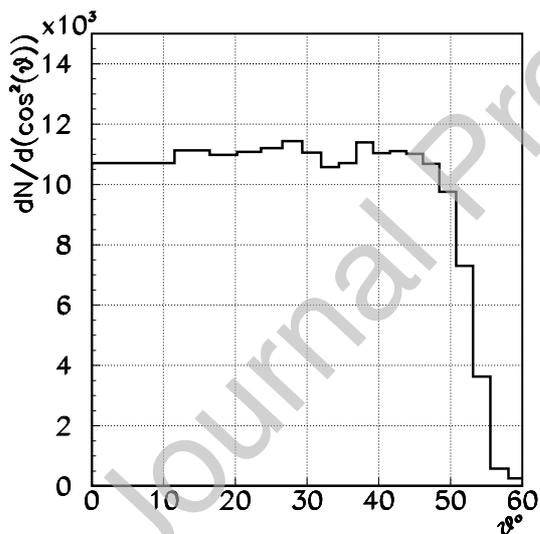


Fig. 3. Zenith angle distribution of showers with a reconstructed energy larger than 15.0 PeV.

The PMT pulses are amplified by pre-amplifiers and sent via 95 m coaxial cables RG58 to the electronics box in the center of each cluster and digitized there. The digital information is stored in the cycle buffer

memory. The memory is stopped, and the data is sent to the central DAQ system in case of a cluster trigger appearance. The trigger condition is the appearance of pulses exceeding the digital threshold (see apparatus description [5]) at 3 or more detectors of a cluster within a time gate of  $0.5 \mu\text{s}$ .

The minimum pulse width 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 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 amplitude calibration of the detectors was carried out in two steps similar to that used at the previous experiment Tunka-25. The details are described in [6].

### 3 Calibration

#### 3.1 Timing calibration

The timing calibration of the detectors is performed using the experimental data from the recorded air showers.

The calibration inside a single cluster consists of a multiple reconstruction of zenith angle  $\theta$  and azimuth

angle  $\phi$  for all the recorded showers, with an analysis of the residual difference between the measured and the theoretically expected delay for 6 peripheral detectors of a cluster. For calibration purposes at this step we use a plane model of the shower front. Modelling a curved shower front demands knowledge of the EAS core position which we reconstruct only at later steps. The difference between plane front and a realistic curved front leads to a larger dispersion of the residuals  $\Delta T_i$  but it does not distort very much the mean value of  $\Delta T_i$  ( $\langle \Delta T_i \rangle$ ) because of an almost uniform core distribution across a cluster area and the limited size of the clusters.

The residual  $\langle \Delta T_i \rangle$  is treated as an additional apparatus shift and added to the calibration shift. Then the procedure of the arrival direction reconstruction is repeated several times till all the detector shifts become less than  $\langle \Delta T_i \rangle = 1$  ns.

The obtained corrections of time shifts are used for a preliminary reconstruction of the EAS core position with a plane model of the shower front, using that single cluster which recorded the largest amplitudes of pulses.

At the second step of the timing calibration we select large showers with more than 8 hit clusters and reconstruct the shower front assuming a curved shape derived from CORSIKA simulations and described in the next section.

The space basement of optical sta-

tions for such events is more than 500 m. Therefore the error of cluster synchronization (about 10 ns) leads to a maximum error in the arrival direction of  $0.4^\circ$ .

Finally the two calibration parameters are *a)* the delays between the central stations of the different clusters and *b)* the delays of the peripheral detectors within a cluster relatively to their central one.

The corrections of the central station delays are obtained applying the multi-cluster procedure for the central stations only to a single cluster, one but with a curved shape of the shower front.

The last correction of the time shifts is made synchronously for all 6 peripheral detectors of a cluster rotating their common plane so that the EAS axis direction measured by each single cluster coincides with the direction derived from a multi-cluster reconstruction with an accuracy better than  $0.5^\circ$ . An example of an EAS front reconstructed after the time calibration procedure is presented in Fig. 4.

### 3.2 Relative amplitude calibration

The amplitude calibration of the detectors was carried out in two steps [6]. The first step is a relative calibration, i.e. a derivation of the amplitude alignment coefficients for all individual detector outputs when the optical detectors were illuminated by the same light flashes.

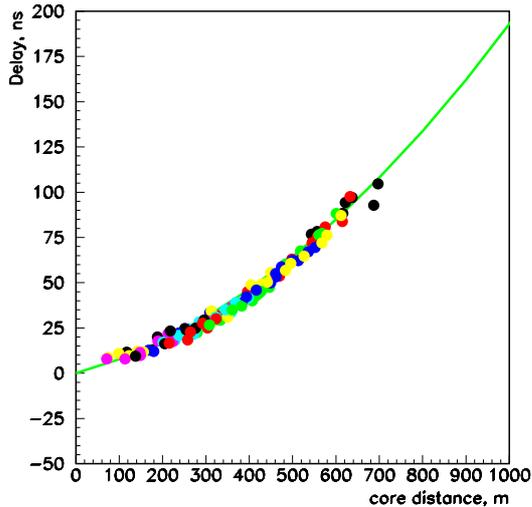


Fig. 4. An EAS front reconstructed from an experimental event,  $E_0 = 6.8 \times 10^{17}$  eV, zenith angle  $\theta = 19.2^\circ$

Differences in gain and quantum efficiency of individual detectors resulted in output signal amplitude variations of a factor 2-3.

As the apertures of all detectors are the same, these coefficients were determined by comparing the amplitude spectra of the EAS Cherenkov light flashes. The residual dispersion after the renormalizing was less than 10%. Due to the stability of the EAS flux, the variation of the coefficient essentially reflects the time drift of the PMT gain as well as the relative atmospheric transparency.

The second step was the absolute calibration, made by normalization of the obtained integral energy spectrum to a reference spectrum. The details of this procedure will be described in section 4.5.

## 4 EAS parameter reconstruction

### 4.1 Fitting the Cherenkov light pulse

The raw data record for each Cherenkov light detector contains 1024 amplitude values  $a_k$  in steps of 5 ns (Fig. 5). Thus each pulse waveform is recorded over  $5 \mu\text{s}$ .

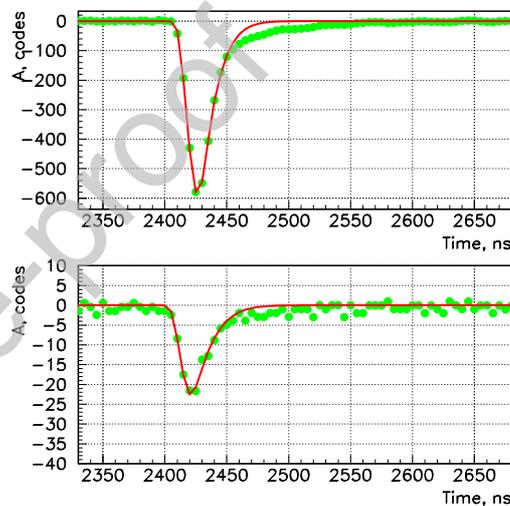


Fig. 5. Experimentally recorded pulses. The upper panel displays a pulse from the high gain channel (anode), the lower panel displays the same pulse recorded with a low gain channel (dynode). Each curve is a fit of the experimental points by expression (1).

The waveform of the light pulse is too complicated to be fitted with any simple function like a Gaussian or gamma function. We have constructed a function which separately approximates front and tail of a pulse [15]. The expression is based on 4 independent variables: the pulse amplitude  $A$ , the time of the pulse

maximum  $t_{max}$ , and  $t_{front}$  and  $t_{tail}$  – the times of the front (pulse reaching  $0.1A$ ) and the tail (pulse falling to  $0.1A$ ).

From these variables we derive:

$$\begin{aligned} x &= t - t_{max} \\ f &= |x/t_{front}| \\ g &= x/t_{tail} \\ h &= \begin{cases} 1.7 - 0.5 \cdot g, & \text{if } g < 0.8 \\ 1.3, & \text{if } g \geq 0.8 \end{cases} \end{aligned}$$

Using these variables the function for fitting the pulse waveform is as follows:

$$a(t) = \begin{cases} A \cdot \exp(-f^{2+0.5 \cdot f}), & \text{if } x \leq 0 \\ A \cdot \exp(-g^h), & \text{if } x > 0 \end{cases} \quad (1)$$

This expression reasonably well approximates the pulse waveform from the level of  $0.1A$  at the front edge to the level of  $0.2A$  at the droop of the pulse. This time range is enough to determine by fitting function (1) such pulse parameters as peak amplitude  $A_i$  and front delay  $t_i$  at the level of  $0.25 \cdot A_i$ . The pulse area  $Q_i$  is measured by digital integration of the waveform starting from the level  $0.05 \cdot A_i$  at the front till the same level at the tail. A fourth pulse parameter is the effective width  $\tau_{eff} = Q_i/(1.24 \cdot A_i)$ . The accuracy of this parameter is better than that of the pulse width (FWHM) used in earlier reports.

An example of a fit of experimental pulses with expression (1) is shown in Fig. 5.

#### 4.2 Arrival direction

Zenith angle  $\theta$  and azimuth angle  $\phi$  of the shower direction are reconstructed by fitting the measured delays with the curve shower front:  $\Delta T = T_i - T_f = R \cdot (R + 500)/(c \cdot F)$ , where  $T_f$  is the estimated delay for a plane front,  $R$  the perpendicular distance from the shower axis in meters,  $c$  the speed of light and  $F$  the third variable parameter (together with  $\theta$  and  $\phi$ ). This approximation is derived from the analysis of simulated showers with CORSIKA. The formula, on the one hand, has a non-zero value of the derivative at  $R = 0$  (conical shape, typical for Cherenkov radiation at short distances from the axis) and on the other hand, has only one shape parameter which is essential for processing of relatively small showers. To obtain  $R$  one needs to know the EAS core position.

#### 4.3 Core position

The reconstruction of the EAS core position is performed by fitting the measured amplitudes  $A_i$  with an amplitude distance function (ADF):

$$A(R) = A(200) \cdot p(R), \quad (2)$$

The shape of the ADF was been studied with CORSIKA simulated events. It has been checked for simulated events in the energy range  $10^{15} - 10^{18}$  eV, for primary protons and iron nuclei, and for zenith angles from  $0^\circ$  to  $45^\circ$ . It cannot be fitted with any simple function. Therefore

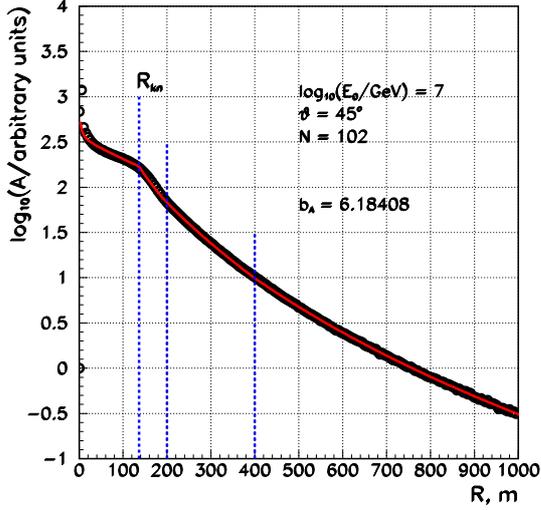


Fig. 6. An example of the ADF of a simulated event fitted with expression 3.

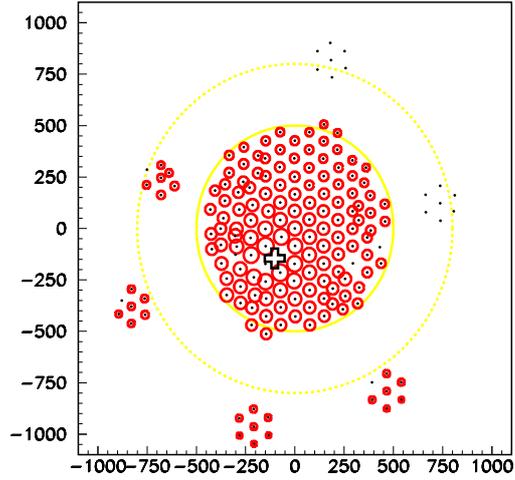


Fig. 8. Example of an experimental EAS core reconstruction. The radius of each station circle is proportional to  $\log Q_i$ . The cross marks the reconstructed position of the shower core.

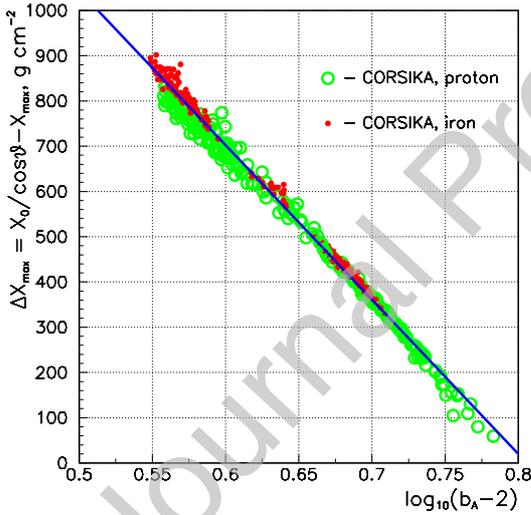


Fig. 7. Correlation between  $b_A$  and the thickness of matter between observational level and the EAS maximum depth.

we have designed a function consisting of four different parametrizations for four different distance ranges (see [16]).

The first one closest to the core is an

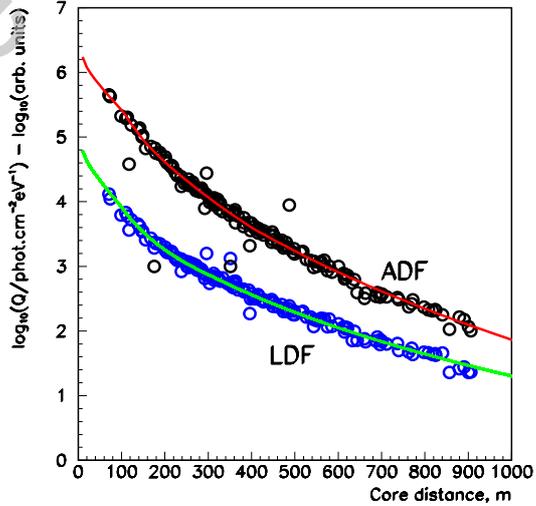


Fig. 9. Pulse amplitudes of the event shown in Fig. 6. Upper curve: fitted with ADF ( expression 3, arbitrary units). Lower curve: fitted with LDF (expression 6).

exponential function with variable parameter  $R_0$  and addition of a pole close to  $R = 0$  m. This parametriza-

tion is changed to a power law function at the variable distance marked as "knee" ( $R_{\text{kn}}$ ). The index of the power law  $b$  is also variable. This function is changed to a Linsley function with a variable parameter  $a$  at the distance range 200 - 400 m. The last parametrization is the same function with fixed value of  $a = 1$ . The function  $p(R)$  is a fit to four different parametrizations with respect to the distance  $R$  to the shower core (in meters):

$$p(R) = \begin{cases} \exp\left(\frac{(R_{\text{kn}}-R)}{R_0}\left(1 + \frac{3}{R+2}\right)\right), & R < R_{\text{kn}} \\ \left(\frac{200}{R}\right)^b, & R_{\text{kn}} \leq R \leq 200 \text{ m} \\ \left(\left(\frac{R}{200} + a\right)/(1+a)\right)^{-b_A}, & 200 \text{ m} \leq R \leq 400 \text{ m} \\ \left(\left(\frac{R}{200} + 1\right)/2\right)^{-b_A}, & R > 400 \text{ m} \end{cases}$$

All four variables in equation (3) ( $R_0$ ,  $R_{\text{kn}}$ ,  $a$  and  $b$ ), describing the ADF shape in different ranges of core distance  $R$  are related to a single parameter of the ADF shape – the steepness  $b_A$ :

$$d = b_A - 5$$

$$D = \log_{10}(d),$$

$$R_0 = 275/d^2,$$

$$R_{\text{kn}} = 145 - 115 \cdot D,$$

$$a = 0.89 - 0.29 \cdot D,$$

$$b = \begin{cases} 2.4 + 2 \cdot (D - 0.15), & b_A \geq 6.41 \\ 2.4, & b_A < 6.41 \end{cases}$$

The ADF steepness parameter  $b_A$  is treated as an independent variable during the minimization procedure. If, however, the core position is far from the dense parts of the array,  $b_A$  is treated as a fixed parameter. In this case its value is derived from the value of  $X_{\text{max}}$ , obtained in turn from the mean width  $\tau_{\text{eff}}$  of Cherenkov light pulses at a distance of  $R = 400$  m. The connection relation  $\tau_{\text{eff}}$  vs.  $X_{\text{max}}$  and  $b_A$  vs.  $X_{\text{max}}$  has been obtained and discussed in [16].

An example of CORSIKA simulated ADF fitted with formula (3) is shown in Fig. 6. Figure 7 presents the result of fitting some hundreds of simulated events for different zenith angles, different energies and different sorts of nuclei listed above as the correlation between  $b_A$  and the thickness of matter between the EAS maximum and the array. An example of core reconstruction is presented in Fig. 8. The appropriate functions ADF (3) and LDF (see expression (6) below) for this event are presented in Fig. 9.

#### 4.4 Energy reconstruction

As a measure of energy we use the light flux density at a distance  $R = 200$  m –  $Q(200)$ . Reconstruction of  $Q(200)$  is made by fitting the measured values of  $Q_i$  with the lateral distribution function (LDF). The new expression used now differs slightly from our previous version described in [17].

$$Q(R) = Q(200) \cdot q(R), \quad (5)$$

The function  $q(R)$  is a combination of three different parametrizations according to the distance  $R$  to the shower core (in meters):

$$q(R) = \begin{cases} \left(\frac{200}{R_{\text{kn}}}\right)^{b_2} \cdot \exp\left(\frac{R_{\text{kn}} - R}{R_0} \left(1 + \frac{3}{R+3}\right)\right), & R < R_{\text{kn}} \\ \left(\frac{200}{R}\right)^{b_2}, & R_{\text{kn}} \leq R \leq 300 \text{ m} \\ \left(\frac{2}{3}\right)^{b_2} \cdot \left(\left(\frac{R}{300} + 1\right)/2\right)^{-b_2}, & R > 300 \text{ m} \end{cases}$$

All three variables in equation (3) ( $R_0$ ,  $R_{\text{kn}}$  and  $b_2$ ), describing the LDF shape in the different ranges of core distance  $R$  are related to a single parameter of the LDF shape – the steepness  $b_Q$ :

$$\begin{aligned} R_0 &= 200 \cdot (b_Q - 2.6)^{1.76}, \\ R_{\text{kn}} &= 100 + 38 \cdot (b_Q - 4.5)^2, \quad b_Q \leq 4.5 \\ R_{\text{kn}} &= 100, \quad b_Q > 4.5 \\ b_2 &= 1.97 + 0.12 \cdot (b_Q - 3.314)^2 \end{aligned}$$

The connection between the EAS energy  $E_0$  and  $Q(200)$  has been obtained from CORSIKA simulations. The result of the simulation using QGSJET-II-04 is shown in Fig. 10. Black points are the mean values of  $Q(200)$  for primary protons, red points are the mean values of  $Q(200)$  for primary iron nuclei. The simulation was made for discrete energies 3, 10, 30, 100, 300, 1000, 3000 and 10000 PeV and zenith angles  $30^\circ$  and  $45^\circ$ . A simplified primary composition was supposed, consisting of equal contributions of protons and iron nuclei ( $\ln A = 2.0$ ), for ener-

gies  $\leq 3 \cdot 10^{17}$  eV. The pure proton composition is supposed for the energy  $10^{18}$  eV in accordance with the results of TA [18] and PAO [19] experiments.

A linear fit of the individual simulated points gives

$$\log_{10}(E_0) = C_A + (0.940 \pm 0.003) \cdot \log_{10}(Q(200)), \quad (6)$$

for fitting over the energy range  $3 \cdot 10^{15} - 10^{17}$  eV and

$$\log_{10}(E_0) = C_B + (0.951 \pm 0.002) \cdot \log_{10}(Q(200)), \quad (9)$$

for fitting over the energy range  $10^{17} - 10^{18}$  eV.

The constant  $C_A$  is obtained from the procedure of absolute energy calibration (by the normalization to the reference CR integral intensity) described at the next subsection. The constant  $C_B$  can be obtained from  $C_A$  and the expressions (8) and (9):

$$C_B = (0.951 \cdot C_A - 0.01 \cdot 17)/0.940, \quad (10)$$

We have analyzed a possible influence of the uncertainty in composition to the calculation of  $E_0$  from  $Q(200)$ . Changing the iron percentage in the composition from 30 % to 70 % changes  $\ln A$  from 1.2 to 2.8 and the value of the coefficients at the expressions (8) and (9) by less than  $\pm 0.01$ . This is one of the sources of the systematic uncertainty in the absolute energy estimation.

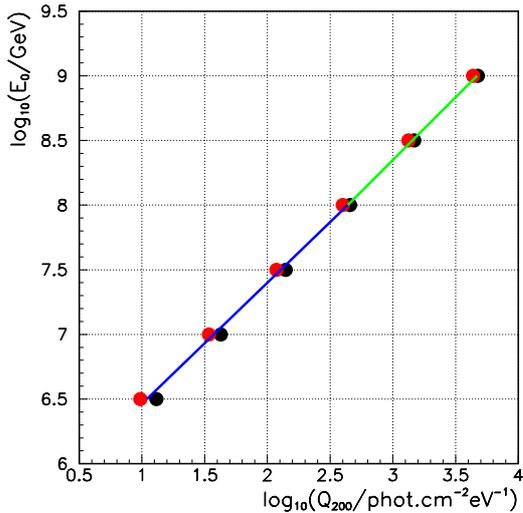


Fig. 10. CORSIKA QGSJET-II-04 simulation of  $Q(200)$  vs.  $E_0$ . Black points are the mean values of  $Q(200)$  for primary protons, red points are the mean values of  $Q(200)$  for primary iron nuclei.

#### 4.5 Absolute energy calibration

To reconstruct the EAS primary energy from the Cherenkov light flux measurements one needs to know the absolute sensitivities of the Cherenkov detectors and the atmosphere transparency. To avoid these problems, the method of normalization of the integral energy spectrum to a reference spectrum is used. The reference energy spectrum was measured by the QUEST experiment [20], [21]. The procedure of the normalization starts by the precise measurement of the EAS (or the primary particle) integral flux for the measured codes (or the relative energy). To measure the integral flux the number of events exceeding a measured relative code is calculated. The integral flux is obtained by dividing this number by the selected effective

area, the selected effective solid angle and the observation time. The so obtained (for each night of Tunka-133 operation) integral energy spectrum is compared at the fixed flux level with the reference spectrum point. This comparison provides the normalisation constant  $C_A$  in expressions (8), used for calculation of the absolute primary particle energy of all the events independently of their EAS core position.

The exact point for normalization is chosen depending on the threshold of the experiment, because it has to have the maximal possible statistics for the events, registered with the efficiency close to 100%. It was  $3 \cdot 10^{15}$  eV for the Tunka-25 array [6] where different PMTs (QUASAR-370) with about 4 times larger photocathode area were used. The normalization energy point for the first 3 years of Tunka-133 operation was estimated as  $6 \cdot 10^{15}$  eV. About 5 years ago the authorities of the nearest villages (situated 3 km from the array site) installed new street lights much brighter than the previous ones, so the level of artificial light background became much higher. Therefore we used a normalization energy of  $10^{16}$  eV for the last 4 years.

The systematic uncertainty in the reconstructed primary energy was estimated in Ref. [21] to be less than 10%.

This systematic error together with the above mentioned uncertainty ( $\pm 0.01$ ) in the coefficients (0.940 and 0.951) in formulae 8 and 9 provides the systematic uncertainty in the

primary energy spectrum which will be shown in Fig. 15.

#### 4.6 Experimental evaluation of the accuracy of the main EAS parameters

The accuracy of the reconstructed shower parameters can be estimated using the well known chessboard method [22]. To use this method, the array is divided into two independent sub-arrays of similar size and configuration. Then the EAS parameters are derived independently with each of the two sub-arrays. The accuracy of any parameter is given by the difference between the two reconstructed values divided by a factor of  $\sqrt{2}$  because they represent two independent experimental determinations of the same shower parameter. Applying this method to the Tunka-133 data, we composed the first sub-array from detectors with odd station IDs and the second one from detectors with even station IDs. The results are shown in Figs 11 and 12.

The upper panel of Fig. 11 shows the errors of the reconstruction of the core position  $R_c$ . In the central part of the array ( $R_c \leq 450$  m) where showers with  $\log_{10} E_0 \geq 15.5$  are recorded with almost 100% efficiency (see section 5), the error in  $R_c$  is less than 8 m. For the outer, sparsely instrumented region ( $450 \text{ m} \leq R_c \leq 800$  m) a 100% efficiency is reached only for  $\log_{10} E_0 \geq 16.5$  with an error in  $R_c$  almost twice of that for the inner region. The lower panel of Fig. 11 shows the relative uncer-

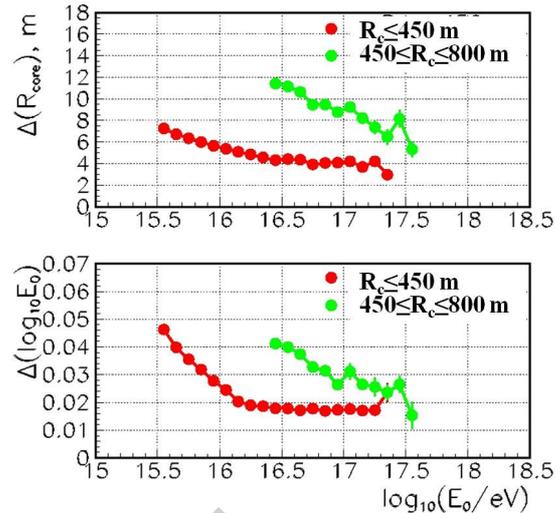


Fig. 11. Upper panel – errors of core position reconstruction. Lower panel – relative errors of primary energy reconstruction.

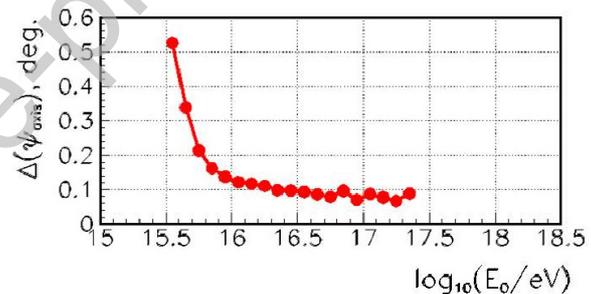


Fig. 12. Error of arrival direction.

tainty in the primary energy  $E_0$ . For the central part of the array, the error in  $\log_{10} E_0$  decreases rapidly from 0.05 at  $\log_{10} E_0 \sim 15.5$  to 0.02 for  $\log_{10} E_0 > 16.0$ . Even for events with their core in the peripheral regions and  $\log_{10} E_0 > 16.5$ , the error is smaller than 0.04. These values are much smaller than the binning of our energy spectra ( $\Delta_{bin} \log_{10} E_0 = 0.1$ ) avoiding a spectral deconvolution of the latter. Fig. 12 shows the error of the arrival direction. For  $\log_{10} E_0 \geq 16$ , it becomes smaller than  $0.12^\circ$ .

## 5 Energy spectrum

### 5.1 Experimental data

Tunka-133 operates in clear moonless nights from October to early April. During the other months, the nights are too short for economical operation and the weather conditions are mostly unsatisfactory. Here we present the data from 7 seasons. The total operation time with good weather conditions is 2175 hrs. The mean trigger rate is about 2 Hz. The number of recorded events is  $\sim 1.4 \cdot 10^7$ .

To reconstruct the differential energy spectrum the number of events inside each bin of 0.1 in  $\log E_0$  is calculated. The differential uncorrected intensity ( $I_{uc}$ ) is obtained by dividing this number by the selected effective area, the selected effective solid angle, the observation time and the energy bin width. We have selected events with zenith angles  $\theta \leq 45^\circ$ .

Fig. 13 shows  $I_{uc}$  for the very dense array Tunka-25 [6], for the dense inner part of Tunka-133 ( $R_c < 450$  m) and for full Tunka-133 ( $R_c < 800$  m). Tunka-25 had a much lower energy threshold than Tunka-133 (it is  $\sim 100\%$  efficient for  $\log_{10} E_0 \geq 15$ ) and can be used to experimentally derive the Tunka-133 efficiency in the overlapping region. One sees that for the inner region ( $R_c \leq 450$  m, red dots) full efficiency is reached at  $\log_{10} E_0 \sim 15.7$  while for the full array, i.e. adding the outer sparsely instrumented regions with 450 m

$\leq R_c \leq 80$  m (blue dots) it is reached only at  $\log_{10} E_0 \sim 16.7$ . In the outer regions the condition for a shower to be recorded was chosen to be two or more hit clusters, since for a single-cluster event there is no measurement of the Cherenkov light flux at a core distance 200 m, which is used for the energy evaluation.

The Monte-Carlo-calculated efficiency of the inner part of Tunka-133 ( $R_c \leq 450$  m) as a function of shower energy is shown in Figure 14 as the ratio of the number of recorded events to the number of generated events. At  $\log_{10} E_0 \sim 15.35$  the MC calculated efficiency (curve) is  $\sim 50\%$  and rises to an almost constant value of 95-100% for  $\log_{10} E_0 \geq 15.8$ , in accordance with the efficiencies derived from the uncorrected intensities shown at Figure 13 (red dots). The decreasing efficiency of  $I_{uc}$  for  $\log_{10} E_0 < 15.8$  is due to the fact that below this energy showers are less efficiently recorded even in the inner, densely instrumented part.

To reconstruct the spectrum for  $\log_{10} E_0 < 17$  (where we are not limited by statistics) we used only events with  $R_c \leq 450$  m, since they have more hits and consequently a better quality than events with the same energy but  $R_c \geq 450$  m. For  $\log_{10} E_0 > 17$  (where according to Fig. 13 also the full array is 100% efficient) we used all events with  $R_c < 800$  m. For the highest points of the spectrum, with progressively low statistics, we doubled the bin size from 0.1 to 0.2 in  $\log_{10} E_0$ . The number of events with  $R_c \leq 800$  m and  $\log_{10} E_0 \geq 17$  is 4224.

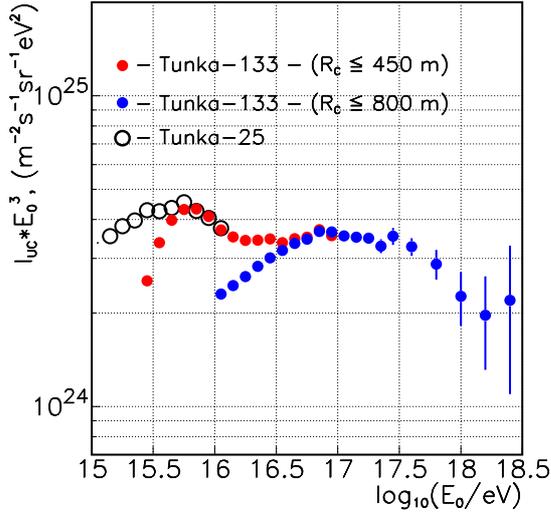


Fig. 13. Differential primary cosmic-ray intensity (uncorrected for registration efficiency)  $I_{uc}$  for two collecting areas:  $R_C \leq 450$  m and  $R_C \leq 800$  m – before combining.

Due an increasing level of light from artificial sources in a nearby village, we had to raise our triggering threshold after the first three years. This affects only the first two points of the spectrum. For the reconstruction of these two points we therefore use only data from the first 3 years of operation.

The resulting differential energy spectrum is shown in Fig. 15 together with the previous spectrum of Tunka-25 [6]. This and the following figures of course show the points with efficiency close to 100% according to Fig. 13 and Fig. 14.

The green contours bracket the possible systematic errors (described above in the section 4.5) due to the absolute normalisation procedure and - to a lesser degree - to the uncertainty of the coefficients (0.940

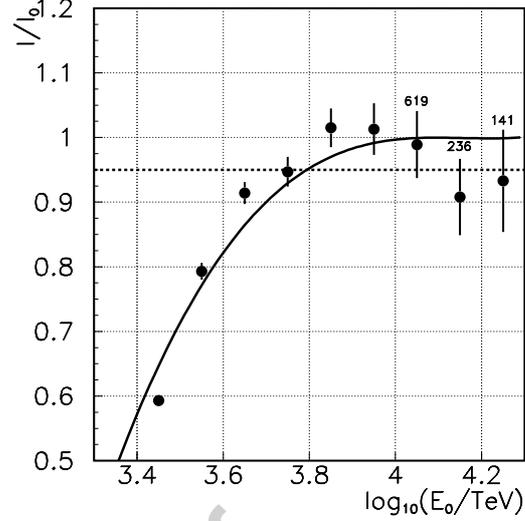


Fig. 14. Energy dependence of the EAS registration efficiency in the threshold energy range. Points are the experimental estimation from Tunka-25 and Tunka-133 data comparison, the solid line is a result of simulation, the dotted line is the efficiency level for the events used for the spectrum reconstruction.

and 0.951) in expressions (8) and (9), connected with the above mentioned uncertainty in the mass composition. A digital representation of the spectrum is presented in Table 1 together with the number of events, statistical and systematic errors.

## 5.2 Features in the energy spectrum

The spectrum of Tunka-133 shows a number of features, that is deviations from a single power law. A power law applies only for spectral regions extending over less than half an order of magnitude. A fit with a doubly broken power law is shown in Fig. 16. At an energy of about  $2 \cdot 10^{16}$  eV, the power law index changes from

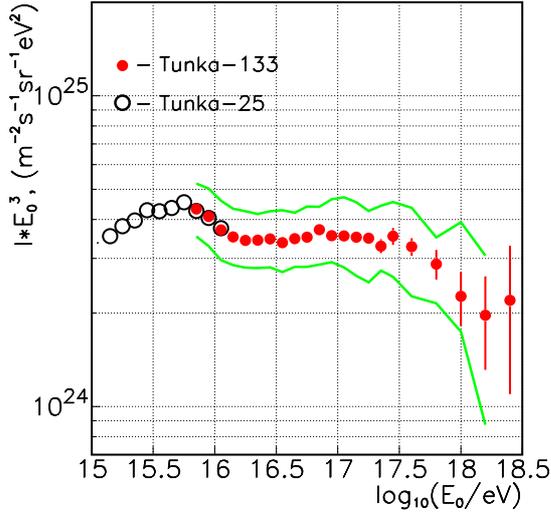


Fig. 15. Differential primary cosmic-ray energy spectrum. Green contours bracket the possible systematic errors.

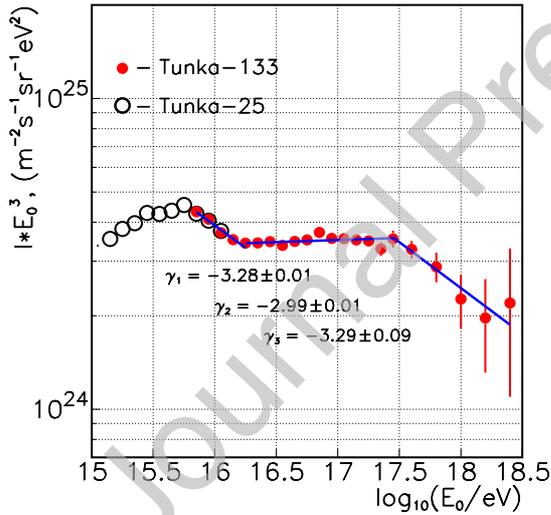


Fig. 16. Differential primary cosmic-ray energy spectrum with a fit of a doubly broken power law.

$\gamma = 3.28 \pm 0.01$  to  $\gamma = 2.99 \pm 0.01$ . This feature was first observed by the KASCADE-Grande experiment [25]. The index can well be used up to  $E_0 = 3 \cdot 10^{17}$  eV. But the statistical probability of a single power

Table 1

All- particle energy spectrum.

$\log(E/eV)$	$N_{events}$	$dI/dE \pm stat \pm sys(m^{-2}sr^{-1}s^{-1}eV$
15.85	70199	$(1.219 \pm 0.005 \pm 0.261) \times 10^{-}$
15.95	41904	$(5.780 \pm 0.028 \pm 1.238) \times 10^{-}$
16.05	53109	$(2.621 \pm 0.011 \pm 0.579) \times 10^{-}$
16.15	31788	$(1.246 \pm 0.070 \pm 0.262) \times 10^{-}$
16.25	19546	$(6.086 \pm 0.044 \pm 1.289) \times 10^{-}$
16.35	12363	$(3.058 \pm 0.026 \pm 0.614) \times 10^{-}$
16.45	7879	$(1.548 \pm 0.017 \pm 0.323) \times 10^{-}$
16.55	4830	$(7.537 \pm 0.011 \pm 1.762) \times 10^{-}$
16.65	3142	$(3.894 \pm 0.069 \pm 0.779) \times 10^{-}$
16.75	2004	$(1.973 \pm 0.044 \pm 0.446) \times 10^{-}$
16.85	1337	$(1.046 \pm 0.029 \pm 0.216) \times 10^{-}$
16.95	806	$(5.007 \pm 0.176 \pm 1.224) \times 10^{-}$
17.05	1604	$(2.504 \pm 0.063 \pm 0.682) \times 10^{-}$
17.15	1004	$(1.245 \pm 0.039 \pm 0.338) \times 10^{-}$
17.25	629	$(6.197 \pm 0.247 \pm 1.616) \times 10^{-}$
17.35	374	$(2.927 \pm 0.151 \pm 0.696) \times 10^{-}$
17.45	254	$(1.579 \pm 0.099 \pm 0.423) \times 10^{-}$
17.60	237	$(5.180 \pm 0.336 \pm 1.639) \times 10^{-}$
17.80	83	$(1.144 \pm 0.127 \pm 0.303) \times 10^{-}$
18.00	26	$(2.262 \pm 0.444 \pm 1.000) \times 10^{-}$
18.20	9	$(4.941 \pm 1.647 \pm 1.647) \times 10^{-}$
18.40	4	$(1.386 \pm 0.693 \pm 0.314) \times 10^{-}$

law representation in this energy range is rather small (about 3%). The main reason of this is one point at  $\sim 7 \cdot 10^{16}$  eV, which is higher than the power law by about 2 standard deviations. This can be seen better if the y-axis is expanded as in Fig. 17. A similar feature at the same en-

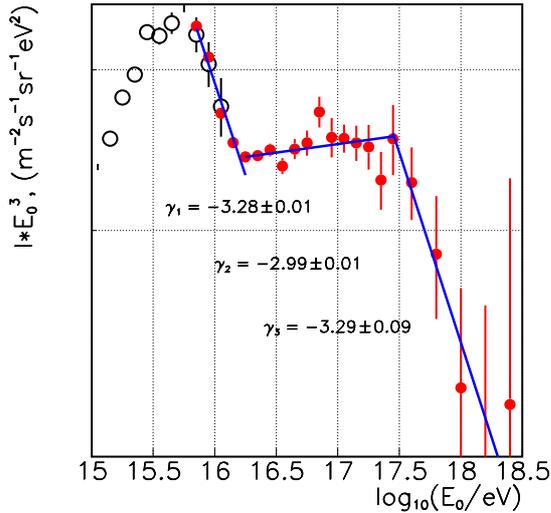


Fig. 17. Representation of the energy spectrum with an expanded scale of the y-axis.

ergy was observed in the experiment GAMMA [27].

The spectrum becomes much steeper with  $\gamma = 3.29 \pm 0.09$  above  $3 \cdot 10^{17}$  eV (the second "knee").

### 5.3 Discussion

In Fig. 18 the spectrum is compared to results from other experiments. The spectra of all the experiments shown in Fig. 18 – KASCADE [28], EAS-TOP [26], Tibet [29], IceTop [30] – are practically indistinguishable at the energy of the first (classical) knee.

There is agreement between the spectra of Tunka-133, KASCADE-Grande [25] and IceTop [30] in the intermediate energy range  $10^{16} - 10^{17}$  eV. We note that the difference between Tunka-133 and KASCADE-Grande spectra at  $E_0$  about  $10^{17}$  eV

can be eliminated by an energy correction of only 4%. The energy shift between Tunka-133 data and IceTop data is slightly larger (about 7%). However, these shifts are smaller than the systematic errors of energy reconstruction in these experiments. The surprisingly good agreement among the spectra was emphasized in [34] and [33].

The paper [33] is devoted to the comparison of energy scales of Tunka-133 and KASCADE-Grande. The spectra were not only compared w.r.t. their form, but the absolute scales of both experiments have been compared via the radio extensions of these experiments named Tunka-Rex and LOPES. The radio detectors have been independently and accurately calibrated. The estimation of the absolute energy calibration uncertainty is less than 10% [33].

For highest energies the Tunka-133 data are in agreement with data from the Telescope Array (TA) [18] and the Pierre Auger Observatory [19], but naturally the Tunka-133 statistics is rather low above  $10^{18}$  eV.

To get more statistics at this energy range, the scintillation counter array Tunka-Grande is presently being constructed at the Tunka-133 site [35]. The total data taking time will be 20 times higher than for the Cherenkov light array. The scintillation detectors will provide information on the number of electrons and muons in the EAS.

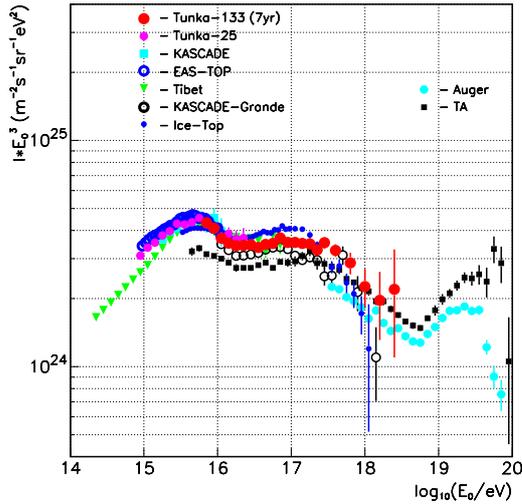


Fig. 18. Comparison of energy spectra obtained at the Tunka site to other experimental results.

## 6 Conclusion

1. The primary CR energy spectrum in the range of  $6 \cdot 10^{15} - 10^{18}$  eV has a number of features: the spectrum becomes harder (the index changes from  $\gamma = 3.28 \pm 0.01$  to  $\gamma = 2.99 \pm 0.01$ ) at  $E_0 = 2 \cdot 10^{16}$  eV and steeper ( $\gamma = 3.29 \pm 0.09$ ) at  $E_0 = 3 \cdot 10^{17}$  eV.

2. In the energy range of  $10^{16} - 10^{17}$  eV, the observed spectrum is consistent with spectra of KASCADE-Grande [25] and IceTop [30].

3. Beyond the energy of  $10^{17}$  eV, the Tunka-133 spectrum is consistent with those from the Telescope Array [18] and the Pierre Auger Observatory [19].

## 7 Acknowledgment

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