The Tunka-133 EAS Cherenkov array - status, first results and plans

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***Abstract*. The new EAS Cherenkov array Tunka-133 with about 1 km^2 geometric acceptance area, is installed in the Tunka Valley (50 km from Lake Baikal). The array will permit a detailed study of cosmic ray energy spectrum and mass composition in the energy range of 10^{15} - 10^{18} eV with a uniform method. The array consists of 19 clusters, each composed of 7 optical detectors with 20 cm PMTs. Since November 2008, the first 12 clusters are in operation, commissioning of the whole array is planned for September 2009. We describe the array construction and DAQ, preliminary results and plans for the future development: deployment of radio-antennas and muon detectors network.**

***Keywords*: EAS Cherenkov array, cosmic rays, energy spectrum and mass composition.**

I. INTRODUCTION

The elaborate study of primary mass composition in the energy range $10^{15} - 10^{18}$ eV is of crucial importance for the understanding of the origin and propagation of cosmic rays in the Galaxy. Since 2006 the work on creation of the EAS Cherenkov array Tunka-133 with a geometric area of 1 km^2 ([**?**], [**?**]) is carried out in the Tunka Valley. Such an array will allow the investigation of cosmic rays in the energy range from 10^{15} to 10^{18} eV by a uniform method. This energy range includes the knee in the energy spectrum at $3 \cdot 10^{15}$ eV, and other features of the spectrum probably connected with the transition from galactic to extragalactic cosmic rays. For one year operation (400 hours) the array will register more than 300 events with energy above 10^{17}eV and the core position inside the array geometry. The use of algorithms of reconstruction of EAS parameters developed for the Tunka-25 array [**?**] will provide an accuracy of the measurement of EAS maximum depth

$X_{max} \sim 25$ g· cm^{-2}. The Tunka-133 array has been detecting Cherenkov light from EAS over the last two years, with a steadily increasing number of detectors (7 detectors – 2006, 28 detectors – 2007 and 84 detectors – 2008) and array effective area. The final array of 133 detectors will be completed by autumn 2009, and internal effective area will reach 1 km^2.

II. TUNKA-133 ARRAY – SHORT DESCRIPTION

The whole Tunka-133 array will consist of 133 optical detectors on the basis of PMT EMI 9350 (20 cm photocathode diameter). Detectors are grouped into 19 clusters with seven detectors in each one – six hexagonally arranged detectors and one in the center. The distance between the detectors is 85 m.

An optical detector consists of metallic cylinder of 50 cm diameter, containing a PMT. The container window is directed to zenith and covered with plexiglas 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 reduces smoothly to about 80% of the vertical one at a zenith angle of 40° and to 50% at 50°. The zenith angle distribution of EAS with energy more than 7 PeV is presented in Fig. 1. It indicates the necessary correction due to the dependence of the efficiency on the angle which is applied during the EAS energy reconstruction. So the new detector allows analyzing events with zenith angles up to 50°.

In addition to the PMT with its high voltage supply and preamplifiers, the container houses a light emitting diode for calibration [**?**] and a detector controller. The controller is connected to the cluster electronics via twisted pair cable by the RS-485 protocol. To provide the necessary dynamic range of 10^4, two analog signals, one from the anode and the other from the dynode are
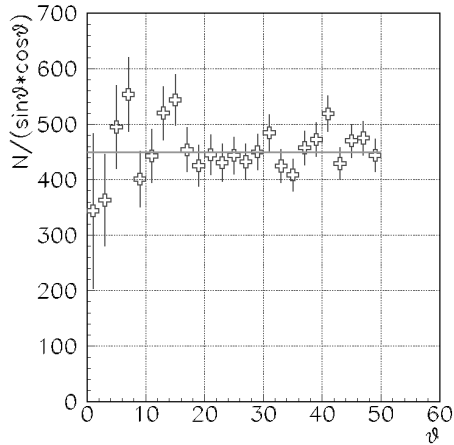
Fig. 1: Zenith angle distribution of events with energy $> 7 \cdot 10^{15}$ eV

Fig. 2: The energy spectrum from Tunka-25 (open circles) and Tunka-133 (filled circles) in the threshold region.

read out. The ratio of amplitudes of these signals is about 30. Both signals are transmitted to the cluster electronics hut via 100 m RG-58 coaxial cables.

The cluster electronics [?] consists of a cluster controller, 4 blocks of four-channel FADCs, an adapter block connected with 7 detector controllers, and the separate temperature controller. The cluster controller consists of an optical transceiver, a synchronization module, a local time clock and a trigger module. The optical transceiver operating at 1000 MHz is responsible for data transmission and formation of a 100 MHz synchronization signal for cluster clocks. The cluster trigger (the local trigger) is formed by the coincidence of at least three pulses from detectors exceeding the threshold within a time window of $0.5\mu s$. The time mark of the local trigger is fixed by the cluster clock. The accuracy of the time synchronization between different clusters is about 10 ns. The FADC boards are designed on the basis of 12-bit 200 MHz ADCs and XILINX microchip FPGAs. All the electronic blocks (except the temperature controller) are implemented in VME standard. Each cluster electronics is connected to the DAQ center with a multi-wire cable consisting of four copper wires and four optical fibers.

III. PRELIMINARY DATA ANALYSIS

The first cluster (7 detectors) has acquired data for about 75 hours from November 2006 to January 2007. Four clusters were operating over next winter, from November 2007 to April 2008. Data have been recorded over 270 hours during clean moonless nights. The average trigger rate was about 0.3 Hz, the number of the registered events was about 300 000. The low energy part of the spectrum is shown in Fig. 2 together with the Tunka-25 spectrum. The energy of 100% efficiency is about $2 \cdot 10^{15}$ eV. It will be possible to decrease the energy threshold of the array by selecting showers with their core position located inside of the cluster geometric area.

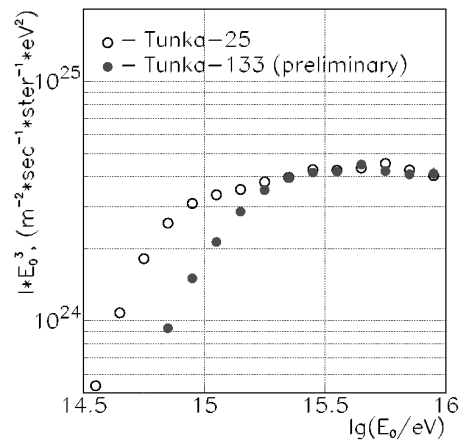Since November 2008, 12 clusters were in operation.

Data from this winter season are still under analysis and the preliminary results will be presented at the conference.

The program of calibration and reconstruction of EAS parameters consists of three main blocks of codes.

1. The first block analyzes the primary data records for each Cherenkov light detector and derives three main parameters of the pulse: front delay at a level 0.25 of the maximum amplitude (t_i), pulse area (S_i) and full width at half-maximum $FWHM_i$.

2. The second block of codes unites the data of different clusters and provides the relative time and amplitude calibration. Data from various clusters are merged to one event, if the time difference for cluster triggers is less than 2 μs.

The time and amplitude calibration and conversion of S_i to light density (Q_i) is provided in the way described in [?].

3. The third block of programs reconstructs the EAS core location, the primary energy and the depth of the shower maximum.

The first method of EAS core location reconstruction is fitting the Q_i (light density at detector i) by the lateral distribution function (LDF) with variable parameter of steepness (P) and photon flux density at a core distance 175 m (Q_{175}). This function – in the form used for Tunka-25 – was first presented in [?], and it was extended to include large distances in [?]. In addition to the traditional method decribed above, a new method of EAS core reconstruction using Cherenkov light pulse $FWHM$ has been developed and implemented in the code. To fit the experimental $FWHM_i$, the empirical width-distance function (WDF) is used. It has a very simple analytic form for $FWHM > 20$ ns:

$$FWHM(R) = 11 \left(\frac{FWHM(400)}{11} \right)^{\frac{R+100}{500}} \tag{1}$$
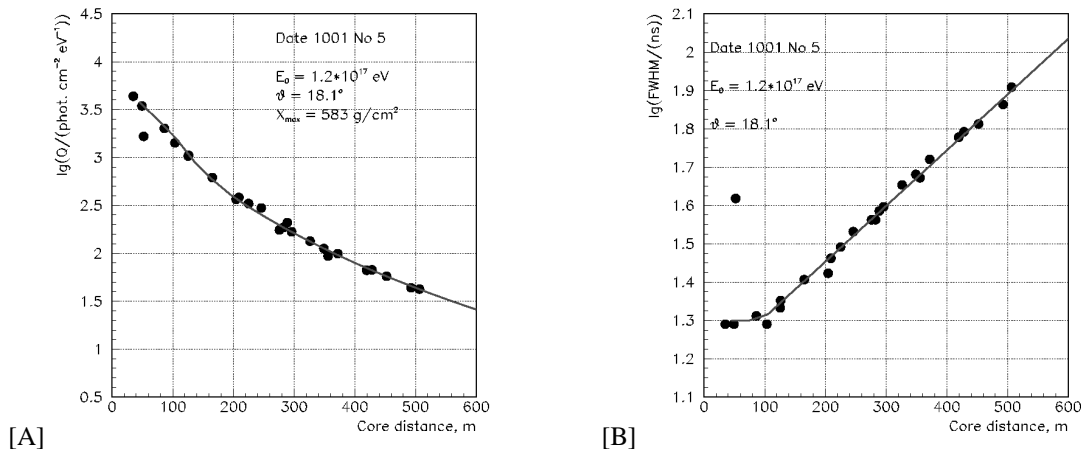
Fig. 3: An example of a reconstructed event.
A. Lateral distribution resulting from fitting the measured light fluxes (points).
B. Dependence of the width of the Cherenkov light pulse on the core distance. Points – experiment, line – approximation by expression (1)

where FWHM(400) is the pulse full width at half-maximum at 400 m from the core.

In more detail, this method of EAS core reconstruction and conversion of FWHM(400) to X_{max} is discussed in paper [**?**], presented at this conference. The EAS maximum depth X_{max} will be reconstructed for each event by two independent methods from LDF steepness P and the parameter $FWHM(400)$. As an example, the LDF and WDF for one event are shown in Figs. 3A and 3B respectively.

It seems that the absence of FWHM random fluctuations and a more simple expression for WDF instead of LDF will allow us applying the new method of EAS core reconstruction not only inside the geometrical area of the array, but also outside (up to a certain distance). It will be possible to check the accuracy of this method up to 1 km core distance by using events with their core (reconstructed by the LDF method) located near the array boundary, using for the WDF method only those parts of the detector which are far away from the core. To check this method up to 1.5 km, the installation of one or two additional clusters at 1 km distance from the center of the array is planned. The possibility to reconstruct events up to 1.5 km from the array center will increase the array effective area for events with energy more than $5 \cdot 10^{17}$ eV by a factor of 5–10 relative to the geometrical area covered by the detectors.

IV. PLAN FOR TUNKA-133 UPGRADING

To increase the effective up-time of the array, we plan to upgrade the Cherenkov array with additional detectors which may register EAS during the day time.

A. Registration of radio signal from EAS

The registration of the radio flux from EAS is – like the registration of Cherenkov light – a calorimetric method which may give information about the energy of primary particles and the depth of the shower maximum with good accuracy. To cross-check this method, we plan to install several radio antennas for common operation with the Cherenkov array. The first 2 high-gain log-periodic antennas were installed in July 2008 (Fig. 4A). The antennas are located at 10 m distance from the cluster electronics box and connected with amplifiers (52 dB and 60 dB respectively) via 20 m LMR-400 coaxial cable. Signals from amplifiers, placed inside the cluster electronics box, are sent to two free channels of Tunka-133 FADC units. These channels (in standard operation mode) are not included in cluster trigger formation, and so the data from the antennas are read out only if the cluster trigger formed by the optical detectors occurs.

In addition to Tunka-133 data storage, data from a third test antenna are also captured at 10-minute intervals on a laptop (using LabView) to allow constant monitoring of changes of the RF environment. The Tunka site shows practically no background in the FM region (88 - 108 MHz) and, with ecxeption of a 1 - 2 MHz interval around 80 MHz, a quite low background in the region >40 MHz (Fig. 4B), which is a range typical of radio air shower detection experiments. MC simulation showed that the signal from $5 \cdot 10^{16}$ eV EAS at a distance ~ 100 m from the EAS core should be clearly visible above background. Experimental data from the winter season is currently under analysis, and preliminary results will be presented at the conference. Additional 4 antennas are planned to be installed in summer 2009.

B. Registration of muons

The deployment of scintillation counters within the Tunka array would provide a cross-calibration of different methods of EAS parameter measurement since all components will be recorded simultaneously. Measuring
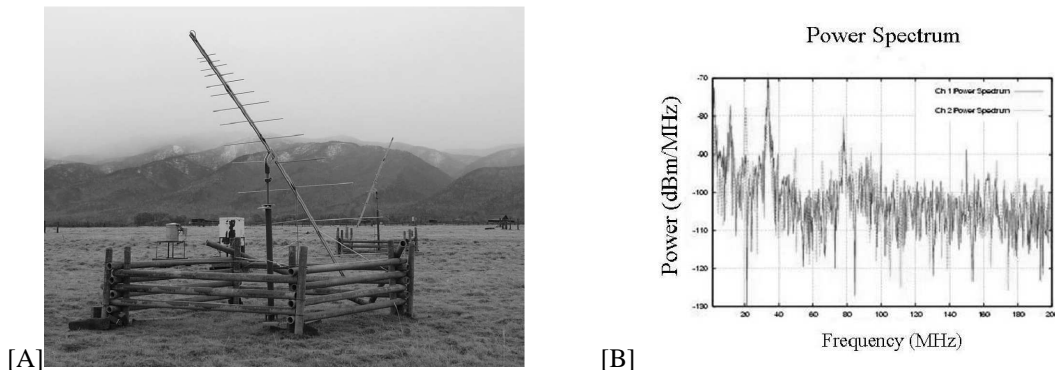
Fig. 4: A. View of the radio antennas.
B. Raw spectral power as a function of frequency for two antennas. The thermal floor at 300 K is expected to be - 114 dBm/MHz.

of Cherenkov light provides the energy of the primary particle and the depth X_{max} of the EAS maximum. The scintillation counters, buried under a layer of 1.5 - 2 m of ground, would allow an estimate of the number of muons in the same events, resulting in a more precise mass composition in the energy range of 10^{17} - 10^{18} eV. These methods were suggested by G. Kristiansen and collaborators already in 1981 [**?**]. The new simulation performed with the AIRES code [**?**] showed that the measurement of the muon number with an accuracy of ($\sim$ 5 - 10%), together with energy and X_{max} with the accuracy achieved at Tunka-133, increases the capability to distinguish Fe from CNO showers. To reach a sufficient accuracy for measurement of the muon number, the spacing of the muon detectors should not exceed 120-150 m. It was shown [**?**] that by using 20 muon detectors with 10 m^2 area placed inside the geometric area of Tunka-133 it is possible to reach an accuracy of about 10% in the total muon number at 10^{17} eV.

V. OTHER RESEARCH ITEMS

A. *Cosmic rays and atmospheric electricity processes*

During the summer season we continue the study of the variation of secondary cosmic rays (electrons and muons) correlated with the variation of the electric field at the ground level and the space-time correlation between lightnings and high energy EAS. In these experiments a water Cherenkov light detector with 10 m^2 area and several radio antennas are used.

B. *Robotic Optical telescope*

For the purpose of continuous sky monitoring, the optical telescope MASTER (Mobil Astronomy System of TElescope Robots) [**?**] will be installed during this summer at Tunka. The main scientific topic of the system is the search for optical radiation from GRBs. For the operation of Tunka-133 this system will give very important information about atmospheric conditions (variation of atmosphere transparency and existence of clouds).

VI. CONCLUSION

The deployment of the Tunka-133 array is approaching its completion. More than 75% of detectors are installed and operating since the last winter season. Commissioning of the complete array is planned in autumn 2009.

The first results show that the array parameters are in a good agreement with the expected ones. Recording of the EAS Cherenkov light pulse waveform for each detector provides a more reliable measurement of X_{max} and opens the possibility to reconstruct EAS with their core outside the array.

Works for upgrading Tunka-133 with day-time operating detectors (radio-antennas and muon scintillation counters) have started.

VII. ACKNOWLEDGEMENTS

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