The Tunka detector complex: from cosmic-ray to gamma-ray astronomy

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Abstract. TAIGA stands for "Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy" and is a project to build a complex, hybrid detector system for ground-based gamma-ray astronomy from a few TeV to several PeV, and for cosmic-ray studies from 100 TeV to 1 EeV. TAIGA will search for "PeVatrons" (ultra-high energy gamma-ray sources) and measure the composition and spectrum of cosmic rays in the knee region (100 TeV – 10 PeV) with good energy resolution and high statistics. TAIGA will include Tunka-HiSCORE (an array of wide-angle air Cherenkov stations), an array of Imaging Atmospheric Cherenkov Telescopes, an array of particle detectors, both on the surface and underground, and the TUNKA-133 air Cherenkov array.

1. Introduction

In recent years ground-based very high energy (VHE) gamma-ray astronomy became the most dynamically developing field in high energy astrophysics. Advantages of gamma rays as information carriers from powerful Galactic and extragalactic sources are due to the fact that in contrary to charged cosmic rays, they preserve their emission direction from sources, and unlike neutrinos, they are easy to detect. Most of the knowledge about sources of high energy gamma rays has been obtained from arrays of Imaging Atmospheric Cherenkov Telescopes (IACT), most prominently HEGRA [1], H.E.S.S. [2], MAGIC [3] and VERITAS [4]. The method of image shape analysis proposed by A.M. Hillas in 1985 [5] allows distinguishing, with high efficiency, Extensive Air Showers (EAS) produced by gamma rays from those initiated by charged cosmic rays. The sensitivity level of presently existing gamma-ray telescopes is optimized for the energy range of 100 GeV - 20 TeV. Gamma-radiation at ≥100 GeV was detected from more than 150 sources of different types, but radiation with energies ≥10TeV was recorded from about 10 sources only. No sources with spectra extending beyond 100 TeV have been detected so far. The so-called 4th-generation IACT array CTA [6] will have substantially higher sensitivity than the existing telescopes in the energy range of up to 100 TeV. For extension towards higher gamma-ray energies it is necessary to construct arrays with lots of telescopes, distributed over an area of a few square kilometers at least. The estimated cost of such an IACT array can be more than 100 million US dollars per square kilometer. So, it is necessary to find more cost-effective experimental solutions which would allow one to have an array with an area of the order of 10 - 100 km² for studying PeVatrons.

To solve many crucial tasks of high energy gamma-ray astronomy as well as of cosmic ray physics we propose to design and to construct the observatory TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) - a complex hybrid detector system. TAIGA will be located in the Tunka valley, about 50 km from Lake Baikal in Siberia, Russia, were since 2009 the full-size Tunka-133 Cherenkov EAS detector is in operation [7-9]. The experience from Tunka-133, it's results on energy spectrum and mass composition of cosmic rays, and the existing infrastructure have been important factors for selecting this location. Common operation of an array of IACTs and a wide-angle array will allow abstaining from the simultaneous measurement of EAS by several closely spaced wide-angle Cherenkov detectors and instead of that increasing the distance between IACTs up to 600 m. The relatively low cost of such an array of largely spaced IACTs, combined with a wide-angle Cherenkov array (cost of a single station of the wide-angle array is only ~1/30 of the cost of an imaging telescope) allows for the necessary huge collection area and for preparing gamma-ray measurements at ~100 TeV and beyond. TAIGA will combine five arrays with different types of detectors:

• The Tunka-133 wide-field (FoV ~2 sr) integrating air Cherenkov array [8]. It consists of 175 detectors including a PMT with a hemispherical-shape photocathode of 20 cm diameter (EMI 9359 or Hamamatsu R1408).

• The low-threshold Tunka-HiSCORE wide-field (FoV ~ 0.6 sr) integrating air Cherenkov array, consisting of detector stations spaced at distances of 75-200m from each other. This array will cover an area of initially ~1 km², and >10 km² at a later phase. The detector stations consist of four PMTs of size either 20 cm or 25 cm in diameter, located close to each other. The PMTs have Winston-cone light-guides, which increase their light collection area by factor of four.

• The Tunka-IACT array – up to 16 IACTs with reflector areas about 10 m² and imaging cameras of 400 PMTs. The FoV of a single telescope will be 8°×8°. The inter-telescope distances will be optimized in the range of 300-600 m.

• The Tunka-Grande array – a net of surface and underground scintillation stations to measure the charged component of air showers. On order to achieve a good rejection of hadron showers at energies ≥ 100 TeV, it is desirable to cover an area of a few 1000 m² with underground muon detectors.

• The Tunka-Rex (Tunka Radio extension) array consists of 47 antenna stations with a spacing of 200 m, spread over about 3 km².

2. TheTunka-133 array

Presently, the Tunka-133 array consists of 175 wide-angle Cherenkov detectors distributed over 3 km^2 area [8]. The energy spectrum of cosmic rays has been reconstructed using data from 5 winter data taking seasons. The resulting differential energy spectrum is shown in figure 1 (left), together with the preliminary spectrum of Tunka-HiSCORE [10]. At energies about 20 PeV, the power-law index changes from $\gamma = 3.23 \pm 0.01$ to $\gamma = 2.98 \pm 0.01$. Above 300 PeV, the spectrum becomes steeper, with $\gamma = 3.35 \pm 0.11$ (the second "knee"). There is a possibility of a more complex description of the second "knee" with a small intermediate increase of the absolute value of the index to $\gamma = 3.06 \pm 0.03$ around 80 PeV. Figure 1 (right) compares the Tunka-133 data to results from other experiments.
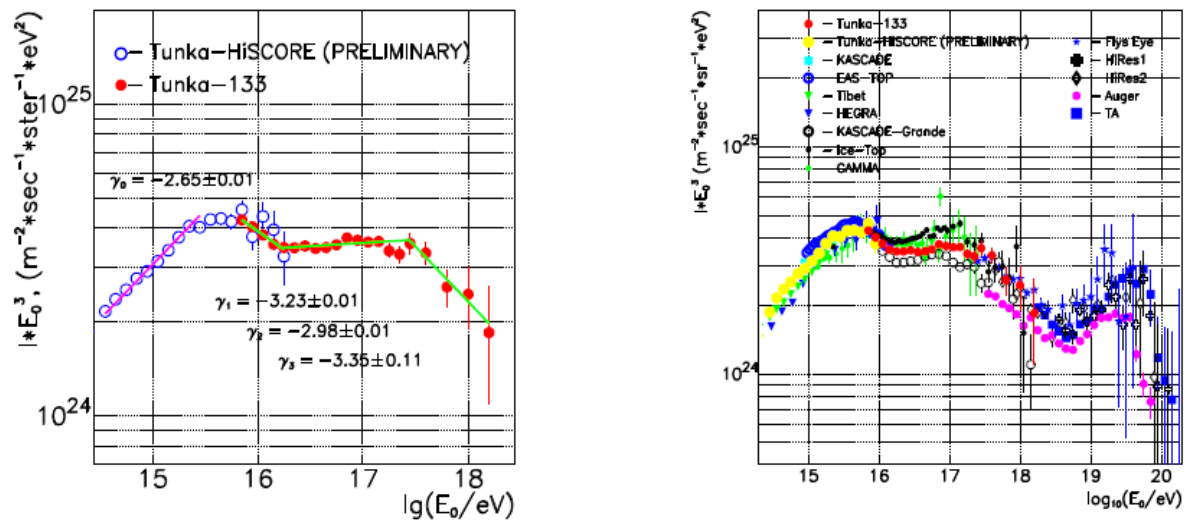

Figure 1. All-particle energy spectrum, left: Tunka data, right: comparison with other experiments.

The methods of EAS maximum depth X_{max} measurement are described in [11]. The experimental dependence of mean X_{max} and mass composition vs. primary energy E_0 are presented in figure 2. The experimental points are compared to the data of the HiRes-MIA experiment [12] and the fluorescent light detectors of Pierre Auger Observatory [13]. One sees agreement of the Cherenkov light results from the Tunka experiment with direct fluorescent light observations. The primary mass composition becomes heavier in the energy range $10-30$ PeV and lighter again in the range $100-1000$ PeV.
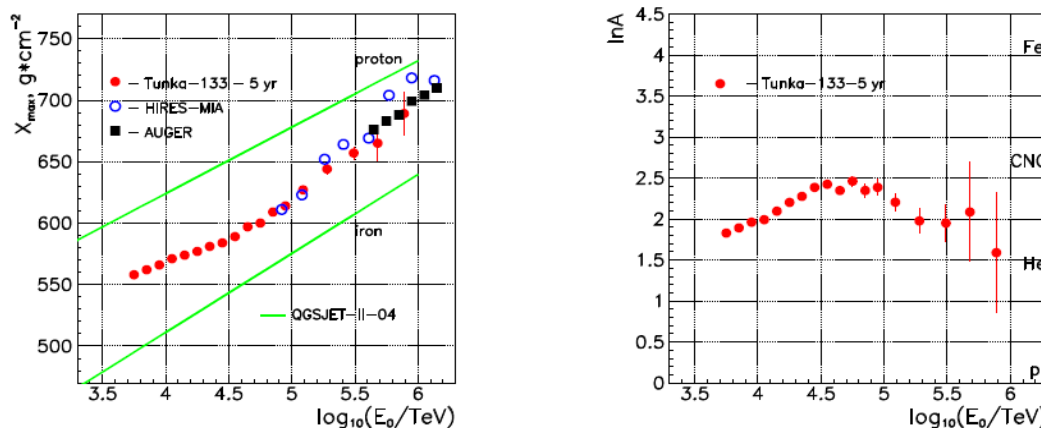

Figure 2. Left: mean depth of EAS maximum; Right: mean cosmic rays logarithmic mass vs. energy.

3. The Tunka-HiSCORE array

The principle of the Tunka-HiSCORE array follows the idea outlined in [14,21]. It is rather similar to the one used for Tunka-133. Again, one samples the Cherenkov light front of air showers. The detector stations measure the light amplitudes and its arrival time differences over a distance of few hundred meters. This approach allows one to reconstruct with high precision the arrival direction and the axis position of the EAS, as well as energy E_0 and height of the shower maximum, X_{max}. The expected accuracy of the core location measurement is 5–6 m, that of the arrival direction about 0.1°, for E_0 it is 10% and for X_{max} – 15-20%. The data can be used to reconstruct in detail the cosmic ray spectrum and its composition, but also provide some gamma/hadron separation. Since the signals from all the four large, high-sensitive PMTs in a HiSCORE station are summed-up, the array has a substantially lower energy threshold than Tunka-133. It should be possible to detect bright gamma-ray sources (as for example the Crab Nebula) at energies ≥ 20 TeV, and charged cosmic rays with energies ≥ 40 TeV.

Tunka-HiSCORE will consist of an array of wide-angle light-sensitive detector stations, distributed with a spacing of 75 – 200 m over an area of a square kilometre in a first phase, and over several tens of square kilometres in the future. A HiSCORE detector stations consist of two boxes. The first type is the optical box (figure 3) with four PMTs, each equipped with a light-collecting Winston cone of 30° half-opening angle pointing to the zenith. A plexiglas plate on top of the cones protects the PMT and the light collector from dust and humidity. Heating prevents the formation of white frost on the plate during the cold season, and a lid opening/closing mechanism is used to protect the PMT from Sun light. The optical boxes house slow-control electronics, high-voltage (HV) systems and a read-out system. For improving the dynamic range of detector, signals are read both from the anode and from one of the dynodes of the PMT.
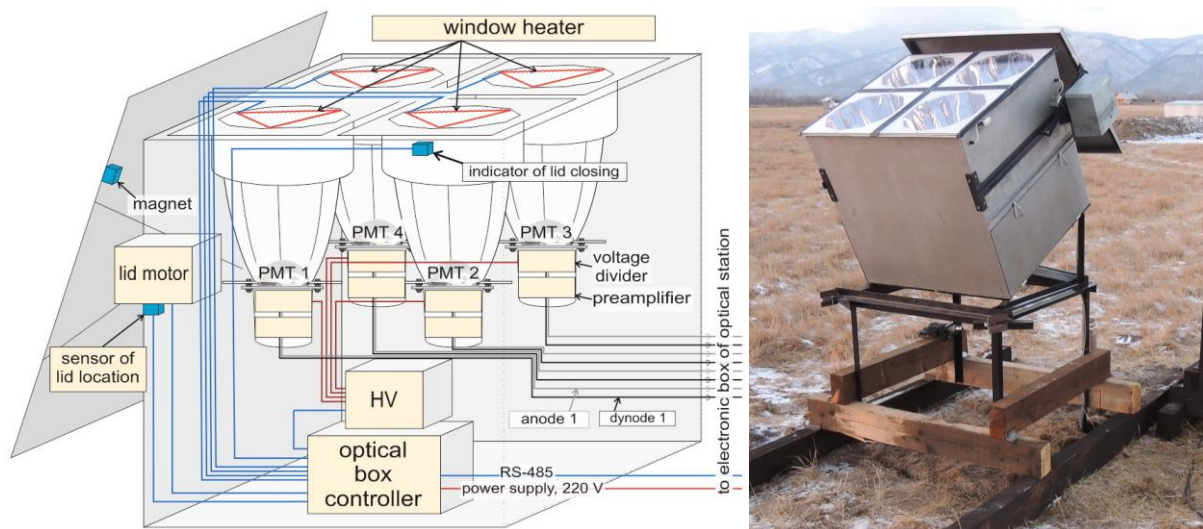

Figure 3. Schematic view (left) and outer view (right) of the Tunka-HiSCORE optical box.

The data acquisition system (DAQ), the slow control for the PMT-high voltage, the environmental control and some auxiliary electronics are placed in a special temperature-controlled box. A fast signal read-out and digitization in the GHz regime is provided by a read-out board with up to 8 channels based on the Digital Ring Sampler DRS 4 chip [15], with a depth of 1024 cells at a resolution of up to 0.2 ns per cell (5 GHz). In order to retain a sufficiently wide read-out window, a sampling frequency of 2 GHz is used, corresponding to a read-out window of 0.5 µs. To acquire the shower data, the high-

gain anode signals of the PMTs are amplified by a custom-made fast preamplifier and then summed-up. To synchronize all stations in the array to sub-nsec precision we use at present a hybrid approach, combining a custom-made synchronization technique (100 MHz clocks distributed over separate fibers from the array center), and the new White Rabbit Ethernet-based technology (with synchronization and Gbit data traffic over a single fiber [16]). The main DAQ-board is designed on the basis of the DRS-4 chip and the FPGA Xilinx Spartan-6. All detector stations and the array center building are connected by single-mode optical fibers. The accuracy of time synchronization is better than 1 ns. The time step of digitization can be changed from 0.2 to 1 ns. The dead-time of the detector station electronics is smaller than 0.5 ms. For the first 9 HiSCORE stations, a fully independent DAQ has been installed, based on two 4-channel DRS-4-evaluation boards, directly synchronized and triggered by White Rabbit [20].

The configuration of the Tunka-HiSCORE stations as of 2014 is shown in figure 5. It comprises 28 detectors at 100 m spacing, forming a super-cell structure. The total area of the setup is 0.25 km^2. To increase the observation time for the gamma-ray source in the Crab Nebula, all optical boxes are tilted towards South by 25 degrees.
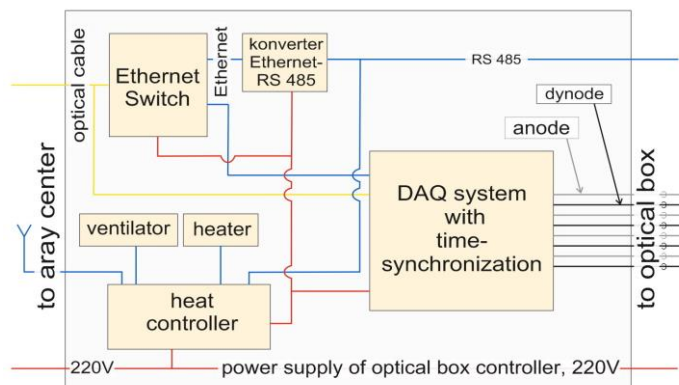

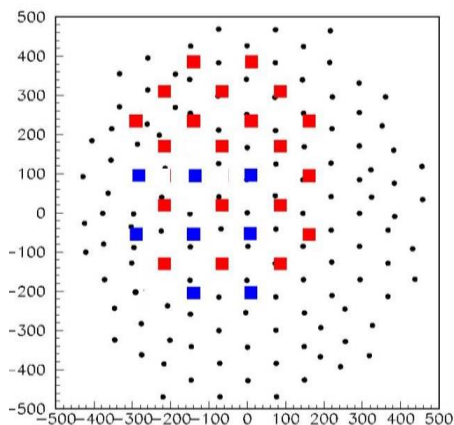Figure 4. Layout of the Tunka-HiSCORE electronics box

Figure 5. Layout of Tunka-HiSCORE (blue squares: stations deployed in 2013, red: in 2014) and the inner Tunka-133 stations (black dots).

The preliminary primary energy spectrum in the range 200 TeV - 20 PeV derived from the 2013 Tunka-HiSCORE data is presented in figure 1. The 2013 configuration consisted of 9 detector stations on a rectangular grid and covered an area of 0.09 km^2.

4. Tunka-Grande: a net of scintillation particle detectors

The main motivation to implement a scintillation array – Tunka-Grande – into TAIGA is to better distinguish the electron-photon component and the muon component of EAS. We intend to use surface scintillation detectors for cross-calibration of the different methods for high energy cosmic-ray studies with the sub-arrays Tunka-133, Tunka-Rex, Tunka-HiSCORE and Tunka-Grande. The underground muon detector will be helpful to determine the type of a primary particle. The possibility to select EAS initiated by gamma rays is based on the fact that the number of muons in EAS induced by charged cosmic rays is on average 30 times higher than in gamma-ray events. Moreover, the muon number in cosmic-ray induced EAS depends on the primary nuclear charge. The distinction of samples enriched with nuclei of certain masses will work well for energies above 100 TeV. However, the overall area of muon detectors S_μ should be at least 0.2-0.3% of the total array area; for Tunka-Grande that means S_μ ~2000-3000 m^2. This large area requires a strict cost reduction per unit of muon detector area.

We have deployed 19 scintillation stations, each with a surface and an underground part (figure 6). The stations are located at distances of ~20 m from the centres of the Tunka-133 clusters. In December 2014 all 19 surface detectors were put into operation. Each of them includes 12 scintillation counters with a size of 80×80×4 cm³ which have been formerly operated as part of EAS-TOP and KASCADE-Grande. At the moment seven of the scintillation stations are equipped with underground muon detectors, each segmented into eight smaller counters. DAQ, synchronization and control systems are the same as for Tunka-133.
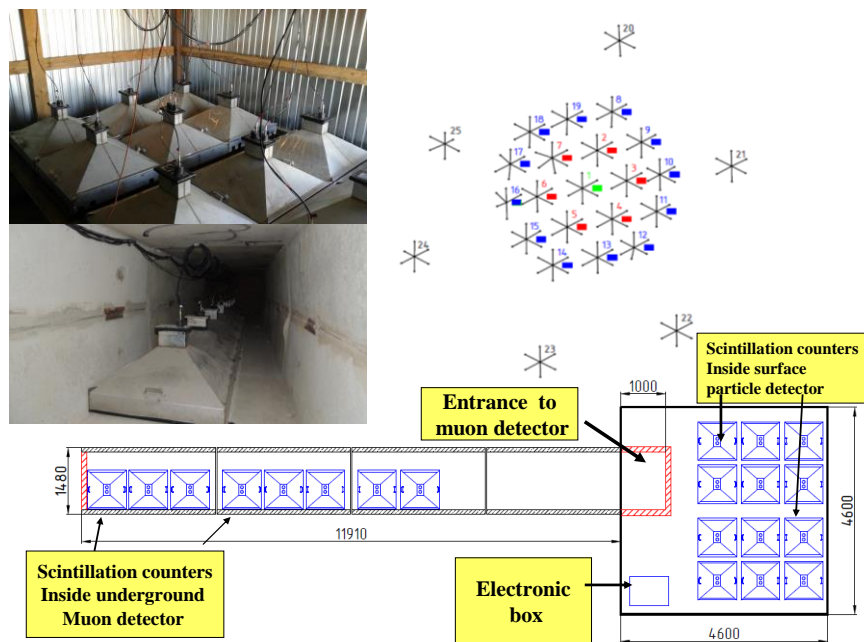

Figure 6. Tunka-Grande, 2014 configuration. Left top: inside a surface detector; Left middle: inside an underground muon detector; Right top: layout of the 19 stations (green and red rectangles - with muon detectors, blue – at present only surface detectors) embedded into the Tunka-133 array; Bottom: layout of a scintillation station.

For the next stage of Tunka-Grande we look for an optimum, cheap design for the muon detectors. The following options will be tested: 1) scintillation detectors of various types; 2) water Cherenkov detectors on the basis of up to 10 m long pipes; 3) Cherenkov detectors in the form of large area water tanks. It is supposed that muon detectors will be bundled into clusters of 30-50 m². Each cluster will be connected to the data acquisition center with a fiber-optics cable. The data acquisition system, the cluster synchronization with its accuracy of 1 ns and the digital trigger system are under design. The possibility to reconstruct the energy and the EAS maximum by Tunka-133 and Tunka-HiSCORE data and to estimate the number of muons will allow us to start searching of point-like and diffuse gamma radiation with energies higher than 1 PeV. The combination of Cherenkov and muon detectors of large area will help us clarifying the change of the mass composition around the knee (at 3 PeV).

5. The Tunka-IACT array

To increase the sensitivity and to decrease the threshold, to organize monitoring of certain sources and – first of all – to separate more reliably gamma-ray initiated showers from the background of charged cosmic-ray initiated showers, it is essential to add an array of Imaging Atmospheric

Cherenkov Telescopes to TAIGA. We have designed and started constructing the first Tunka-IACT, a prototype for the full array. We plan to implement a net of IACTs into TAIGA. The reflectors of these telescopes will have an area of ~10 m^2, and a focus of 4.75 m. We are designing imaging camera matrices consisting of ~400 PMTs, with a field of view of 8×8 degrees and a pixel angular size of 0.36°. Preliminary simulation results show that the joint operation of the wide-angle Cherenkov array HISCORE and a system of IACTs can be a very effective, inexpensive and a fast way to extend gamma-ray astrophysics into the yet unexplored super-high energy domain. Moreover, the IACTs improve the sensitivity at the lower part of the HiSCORE target region. The basic idea is that the two arrays (Tunka-HiSCORE and Tunka-IACT) will work in a coincidence mode and will complement each other: by using the timing and the imaging methods, showers with high precision can be measured. The results of reconstruction of core position and arrival direction of coincident EAS events from the HiSCORE array (expected accuracy of core location ~5-6m and arrival direction ~0.1 degree) will help an IACT in rejecting the high energy background events on large impact parameters of up to 300-500 m. On its turn, the IACT, observing a concrete strong source in the sky, for example the Crab Nebula, can with high efficiency tag the coincident high energy gamma event candidates, which can be used by the Tunka-HiSCORE array for training selection algorithms and improving its gamma/hadron discrimination. It is particularly important that the distance between the IACTs can be made considerably larger than for H.E.S.S., MAGIC, VERITAS or CTA which are not combined with timing arrays. Actually, for an array of 1 km^2 area, only 4-9 IACTs (the number will be specified in the course of further simulations) will be needed. Due to a dedicated, optimised design of the TAIGA configuration, the total cost of such a hybrid array can be kept an order of magnitude lower than the cost of traditional IACT configurations covering the same area but built exclusively with classical, narrow-angle IACTs.

6. The Tunka-Rex array

Tunka-Rex is a radio extension of the Tunka-133 air-Cherenkov array and the Tunka-Grande scintillation array. Every cluster of Tunka-133 includes one antenna station. Recently, for each scintillation station one additional antenna station has been deployed. These antennas measure the radio emission generated by the electromagnetic air-shower component. One major advantage of the radio detection is that it is not restricted to clear nights, as the air-Cherenkov detection. However, the threshold for radio detection is higher. The efficiency becomes comparable to the other detectors only around 10^{18} eV, exactly at those energies for which Tunka-133 is limited by low statistics. Consequently, when triggered in future by Tunka-Grande around the clock, the total statistics at the highest energies could be increased by an order of magnitude.

Each antenna station consists of two orthogonally aligned SALLA antennas, an economic and robust antenna type [17]. The antennas are connected in slave mode to the DAQ of Tunka-133 and Tunka-Grande, respectively. This means that Tunka-Rex is triggered externally, and the radio signal is read out simultaneously with the other detectors. In this way automatically hybrid events are obtained. The first two years of data from 2012 to 2014 are used for cross-calibration: The radio reconstruction of the energy and the shower maximum is compared to the air-Cherenkov reconstruction to check the precision of Tunka-Rex. Preliminary results indicate that at least the energy precision is competitive with Tunka-133 [18].

As a next step, the radio measurements can be combined with the particle detectors to increase the total accuracy for the air-shower parameters: While antenna arrays provide a calorimetric measurement of the electromagnetic component and good sensitivity to the longitudinal shower development [19], measurements of the secondary electrons and muons at ground give a complementary access to the energy and mass composition of the primary particles. In future, this concept can easily be applied to the larger muon array of TAIGA by installing additional antennas.

7. Conclusions

In 2014, the TAIGA collaboration has continued the construction of an array complex of hybrid detector systems. The goal is to search for new local Galactic sources of gamma rays with energies higher than 20-30 TeV. We will also study signals from the nearby extragalactic sources Mrk421 and Mrk-501 in order to investigate the gamma-ray absorption by intergalactic background radiation and to search for axion-photon transitions. The study of gamma radiation in the high-energy range is of interest not only for astrophysics, but also for testing theories predicting a violation of Lorenz invariance and for searching for super-heavy dark matter. Joint operation of the first Cherenkov telescopes of the IACT and the HiSCORE arrays in the energy range of 30-100 TeV will yield sensitivities of the order of 10^{-12} erg cm^{-2} s^{-1} (requiring detection of 50 events in 500 hours of observation). That would give us a good opportunity to measure the energy spectrum of gamma rays from the Tycho SNR, a main PeVatron candidate. For TAIGA – placed at 53° N/L – this source may be observed during more than 200 hours per year, given 50% of good weather condition. This sensitivity level would allow us searching for signals from the sources observed by IceCube as neutrinos, if these sources have Galactic origin, and would allow a survey for new PeVatrons.

Acknowledgments

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