The Taiga project

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Abstract. The TAIGA project is aimed at solving the fundamental problems of gamma-ray astronomy and physics of ultrahigh energy cosmic rays with the help of the complex of detectors, located in the Tunka valley (Siberia, Russia). TAIGA includes a wide-angle large area Tunka-HiSCORE array, designed to detect gamma-rays of ultrahigh energies in the range $20 - 1000$ TeV and charged cosmic rays with energies of 100 TeV $-$ 100 PeV, large area muon

detector to improve the rejection of background EAS protons and nuclei and a network of imaging atmospheric Cherenkov telescopes for gamma radiation detection. We discuss the goals and objectives of the complex features of each detector and the results obtained in the first stage of the HiSCORE installation.

1. Introduction

Over the last decade, the ground-based high energy gamma-ray astronomy became the most dynamically developing field in very high energy (VHE) astrophysics. Detection of gamma rays as messengers from powerful processes in Galactic and extragalactic sources has some advantages compared to detection of charged cosmic rays since they keep 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), the most famous HEGRA [1], H.E.S.S. [2], MAGIC [3] and VERITAS [4]. The method 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 next generation of IACTs is optimized for the energy range from 100 GeV up to tens TeV [6]. Gamma radiation with energies above 100 GeV was detected from more than 150 sources of different types, but gamma rays with energies higher than 10 TeV are detected only from about 10 sources. The detection of sources of hard gamma rays with a spectrum up to several hundreds TeV would be direct evidence of acceleration of cosmic rays in these sources up to the knee in the all particle cosmic ray spectrum. Such galactic PeV accelerators, or Pevatrons [7], have not been detected up to now. An important argument in favor of the search of the gamma-ray with energies above 100 TeV beacame the detection of neutrino with PeV energies by IceCube [8]. However, to access the energy range from 10 TeV up to several 100 TeV, a detection area of the order of 10 km^2 or more is required. Alternatively to imaging gamma telescopes, the shower-front sampling technique allows to install large effective areas and also naturally provides large viewing angles of the instrument. Its operating principle is based on the sampling of the density and timing (arrival-time and spread) of the air shower-front with distributed arrays of detector stations [9]. The TAIGA (Tunka Advanced Instrument for Gamma-ray and cosmic ray Astrophysics) is a new hybrid detector system for ground-based gamma-ray astronomy for energies from a few TeV to several PeV, and for cosmic-ray studies from 100 TeV to several hundreds of PeV. TAIGA will also be located in the Tunka valley, where since 2009 the Tunka-133 Cherenkov EAS detector is in operation. The TAIGA observatory includes HiSCORE – an array of wide-angle integrating air Cherenkov stations, furthermore an array of IACTs, an array of particle detectors, both on the surface and underground, and the Tunka-133 EAS detector. Tunka-133 detects the Cherenkov radiation emitted in the atmosphere by charged EAS particles and currently consists of 175 optical detectors located on an area of 3 km^2 [10]. The individual stations consist of single large PMTs (diameter 20 cm or 37 cm).

2. Tunka-HiSCORE

Tunka-HiSCORE represents an array of wide field of view (FOV) (~0.6 sr) integrating air Cherenkov detector stations, placed at distances of $150 - 200$ m from each other, covering an area of initially ~1 km², and ~100 km² at a later phase of the experiment. Each station consists of 4 neighbored PMTs of size either 20 cm or 25 cm in diameter. The PMTs have Winston-cone shape light-guides, which increase their light collection area by factor of four (see figure 1). DAQ and time synchronization system consists of 8-channel optical station board (OSB) for digitization of signals from anodes and dynodes of 4 PMTs of the optical station and synchronization boards (SB) placed in the DAQ center. All boards are designed on the basis of DRS-4 chip and FPGA Xilinx Spartan-6. OSBs and SB are connected via single-mode optical fibers. To synchronize all stations of the array to sub-ns precision 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 are used [11].

The accuracy of time synchronization is <1 ns. The dead time of OBS is smaller than 0.5 ms. Methods for gamma-ray and cosmic-ray data reconstruction for HiSCORE are similar to ones used for Tunka-133. The PMT outputs are summed up. The detector stations measure the light amplitudes and their arrival time differences over a distance of few hundred meters. This approach allows one to reconstruct with a high precision the arrival direction and the axis position of the EAS as well as the energy E_0 and shower maximum height X_{max}. The expected accuracy of the core location measurement is $5-6$ m, that of the arrival direction about 0.1 degree, for primary energy, $\sim 10\%$ and for $X_{max} \sim 15-20\%$ [12]. The data can be used to reconstruct in detail the cosmic ray spectrum and its composition and will also improve gamma/hadron separation.

Figure 1. The Tunka-HiSCORE optical station. Additional window: the layout of one PMT segment.
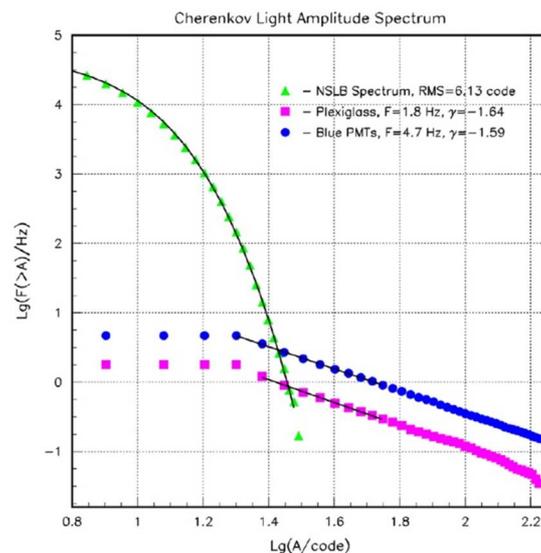
Figure 2. Integral amplitude spectra of the night sky and Cherenkov light flashes from EAS. Triangles: NSLB spectrum. Squares: spectrum from the OS covered with plexiglass. Circles: spectrum from the OS without plexiglass. Errors are within the data points [13].

The integral amplitude spectrum of Cherenkov light flashes from air showers obtained during first tests of HiSCORE optical station (OS) is shown in figure 2 [13]. The spectrum of the night sky light background (NSLB) fluctuation from summator is also given. The value of the sky background fluctuations in RMS units is 6.13, which corresponds to a voltage of 9.2 mV.

From 2013 till the end 2014, Tunka-HiSCORE operated as a 9-station prototype array. The array was arranged on a regular grid of 3×3 stations, with a side length of 300 m [12]. During first experimental series the test with a bright wide-angle LED light source ~200 m outside the array has been performed to check single station performances and full array event reconstruction quality [11]. For the calibration experiment, 45°-inclined mirrors were installed on top of the stations. The event reconstruction precision estimate is obtained by fitting the relative trigger times of the 9 stations: RMS < 0.5 ns. The EAS reconstruction with the HiSCORE-9 prototype with model fit gave RMS ~ 0.6 ns.

The configuration of the Tunka-HiSCORE stations as of 2014 is shown in figure 3 [12]. 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 Crab Nebula, all optical boxes are tilted towards South by 25 degrees. During the winter season 2014-2015, the main task was to adjust the detector and ensure reliable operation.

3. Tunka-GRANDE

The timing array of Tunka-HiSCORE alone has a poor gamma-hadron separation at low energies (10–100 TeV), with a quality factor of the order of one below 100 TeV and only reaching 2 above few

hundreds TeV. To improve the selection efficiency, an underground muon detector is foreseen to determine the type of a primary particle.
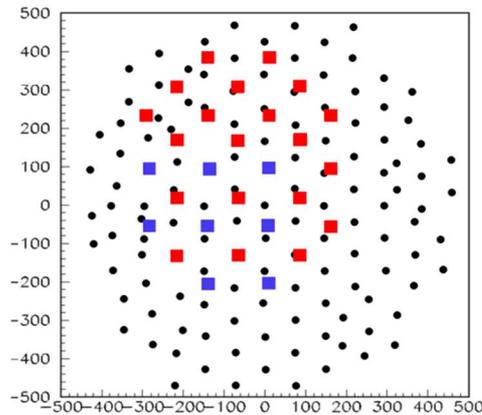
Figure 3. The layout of the Tunka-HiSCORE as of 2014-2015. Black circles: Tunka-133 EAS array; black squares: HiSCORE as a 9-station prototype array; red squares: engineering array (2014 – 2015).
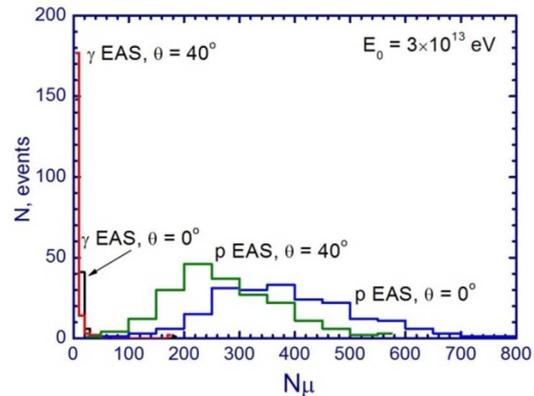
Figure 4. The distribution of EAS with primary energy $E_0 = 3 \times 10^{13}$ eV produced by protons and γ-quanta (2) over the number of muons for zenith angles θ = 0° and θ = 40° at the altitude of observation.

To formulate the main requirements for the muon detectors of the Tunka-HiSCORE facility, preliminary calculations were performed using the CORSIKA program, version 6.990 (FLUKA 2011.2+SIBYLL 2.1 models of interaction; EGS4 for electromagnetic interactions). The standard U.S. atmospheric model was used, and the Earth's magnetic field was disregarded [14]. The threshold energies of the secondary particles were 100 MeV for hadrons and muons, 2 MeV for electrons, and 1 MeV for γ-quanta. The altitude of observation was 150 m above sea level. EAS from primary protons and γ-quanta of cosmic rays with fixed energies $E_0 = 10^{13}$, 3×10^{13}, and 10^{14} eV were simulated for zenith angles θ = 0°, 20° and 40°. For each set of parameters, 200 showers were simulated. The simulated distributions over the number of muons in showers from primary protons and γ-quanta with $E_0 = 3 \times 10^{13}$ eV (zenith angles, 0° and 40°) are shown in figure 4.

As seen from the figure, EAS from protons and γ-quanta are separated reliably. The number of muons at this energy is hundreds of particles on average, so the area of the muon detector must be at least $0.2 – 0.3\%$ that of the entire facility in order to organize multiple coincidences [14]. Therefore, the overall area of shielded muon detectors should be $2000 – 3000$ m^2 of the total area of the Tunka-HiSCORE EAS detector (1 km^2). To suppress the background from γ-rays in ten times relative to the signal from muons, the muon detectors must be buried under a layer of soil 5 – 10 rad. units (1 – 2 m of bulk soil).

For the first stage of the muon array, scintillation detectors formerly operated as part of the EAS-TOP and the KASCADE-Grande arrays are used [12]. This so-called Tunka-GRANDE detector consists of 19 scintillation stations, each of them with a surface and an underground part. The stations are located at distances about 20 m from the centers of the Tunka-133 clusters. Each station includes 12 scintillation counters (80×80×4 cm³ each) with a total area of 8 m^2 size and is equipped with underground muon detector with 8 identical counters in each with total area 5 m^2. The electronics of the scintillation systems are similar to those of the Tunka-133 array and are packed into containers along with ground-based particle counters.

4. The Tunka-IACT

The key advantage of the TAIGA gamma-ray observatory is the hybrid detection of EAS Cherenkov radiation by the wide-angle array Tunka-HiSCORE and the narrow-angle imaging detectors Tunka-IACT [15]. At present, the first prototype of the telescope is being deployed in the Tunka valley. Mirrors of the telescope will have an area of about 10 m^2, and a focal length of 4.75 m. The camera

will consist of 547 photomultipliers with the total field of view (FOV) 9.72°, and the FOV of one pixel is 0.36°. Preliminary results of simulations show that common operation of the HiSCORE array and a net of IACTs can be a very effective, inexpensive and quick way to expand gamma-ray astronomy in the unexplored ultrahigh energy region, as well as to increase the sensitivity of HiSCORE at lower energies and to improve the reliability of separating gamma-initiated EAS against the background of charged cosmic rays. The timing detectors allow increasing the distance between the telescopes since they deliver part of the information which otherwise could be only obtained from IACT stereo operation. The basic idea is that the two setups will complement each other by combining time measurements of showers with shower imaging [15]. It gives the possibility to increase the spacing of our telescopes to about 600 m (see figure 5). The showers are seen by only one telescope at a time, but the reconstruction of these EAS from the HiSCORE timing array provides an information about the core position and incident angle of the shower front; this enables an increase of telescope spacing without loss of gamma-hadron separation power and therefore makes it possible to cover large areas with fewer telescopes [16].
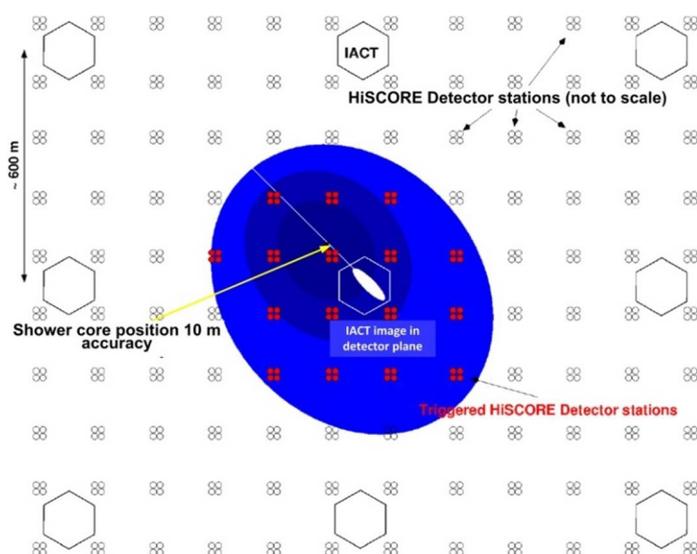
Figure 5. Principle for the combination of IACT and shower front sampling array observation [16]
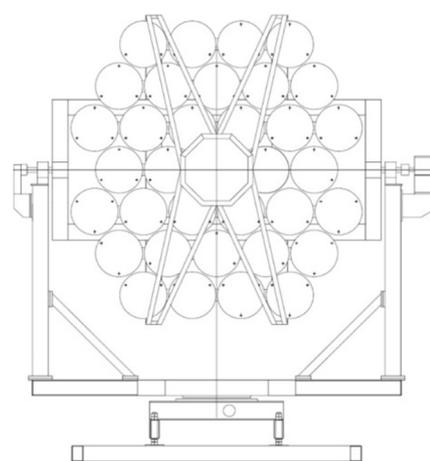
Figure 6. Mechanical design of the first TAIGA imaging telescope.

Each telescope will be composed of a mosaic, 34-segment mirror in Davis-Cotton design, with a 60 cm diameter of individual mirrors. The full diameter of the mirror is 4.3 m, its focal length 4.75 m (see figure 6). At present, the camera with its 547 hexagonal-shaped pixels on 14 hexagonal rings around a central pixel (figure 7a) is being assembled.

As a photodetector, we use the XP1911 PMT with a window of 15 mm diameter. Each PMT is equipped with a Winston cone with an entrance size of 30 mm and an exit spot of 15 mm diameter. The sensitive area of the camera has a diameter of about 81 cm. The entire array of pixels is divided into clusters of 28 PMTs in each. Each cluster includes an electronic board MAROC, the basic element of which is a 64-channel chip ASIC MAROC3 [17] (see figure 7b).

In the figure 7b, the layout of a cluster block with 28 photomultipliers is shown. Such a block is the basic camera unit. Structurally, the electronics of the base block is divided into several boards: four divider boards of the 7 PMT groups (7HEX), four PMT power supply plates, four daughter plates with the DAC for the high-voltage source control, and the ADC for the measurement of the PMT current and signal processing carried out by a PMT DAQ board based on MAROC3.

5. Conclusions

The TAIGA Collaboration made a significant progress towards creating a new observatory for gamma-ray astronomy of ultrahigh energies in Tunka valley. The observatory is targeted to the search

of gamma-ray sources with PeV energies and the study of the flux of UHE primary cosmic rays on the basis of a new approach. With the hybrid detector concept, combining the air Cherenkov timing-array technique with the air Cherenkov imaging technique, TAIGA will deploy a unique detector, optimizing the sensitivity to gamma-rays above 10 TeV.
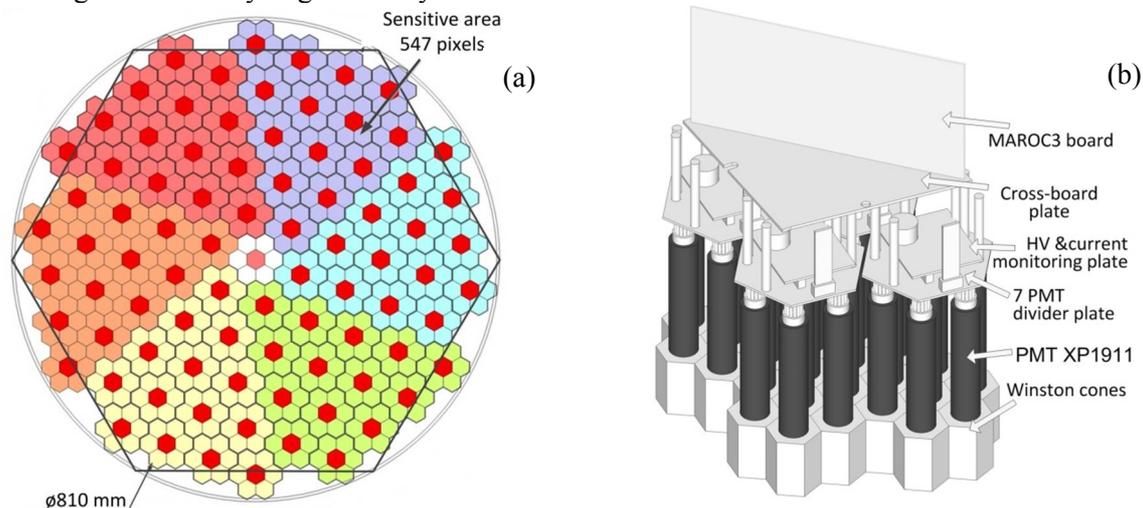
Figure 7. a) The matrix of pixels of the Tunka-IACT camera. b) The basic PMT block of TAIGA-IACT camera.

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