Commissioning the joint operation of the wide angle timing HiSCORE Cherenkov array with the first IACT of the TAIGA experiment


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The first IACT as part of the gamma and cosmic-ray experiment TAIGA was installed in the Tunka Valley near Lake Baikal in fall 2016. In the following months different systems of the telescope were put into test operation. We started the commissioning phase of operating the telescope in time coincidence with the wide angle integrating air Cherenkov HiSCORE array, which for the time being comprises 28 operational stations. We anticipate that the hybrid operation of the non-imaging and imaging telescopes will lead to a cost-efficient, highly sensitive detector operating in the energy range from 30-50 TeV till several PeV. Here we want to report on the first test results of operating the prototype hybrid array. We will focus on the analysis of background cosmic ray flux, count rates, energy and angular resolutions, shower core position reconstruction for coincident events, comparing these with expectations from MC simulations.
1. Introduction

For the multi-TeV energy range of gamma-quanta (≥30 TeV) there are fundamental questions with no answer up to now, and first of all this is the question on the Galactic cosmic ray origin with energies around 1 PeV, close to the classical knee in the all-particle energy spectrum. It should be noted that the highest photon energies measured to date are as much as 80 TeV [1]. A new multi-TeV gamma-ray observatory can uncover the origin of Galactic cosmic ray acceleration.

The gamma-ray observatory TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) is intended to register gamma rays and charged cosmic rays in the energy range of $10^{13} - 10^{18}$ eV [2]. The installation will include a network of wide field of view (angle of view 0.6 sr) timing Cherenkov light stations (TAIGA-HiSCORE, High Sensitivity Cosmic ORigin Explorer), and up to 16 imaging air Cherenkov telescopes (TAIGA-IACT) with the shower image analysis (FOV is $10^\circ x10^\circ$), covering an area of 5 km$^2$, and the muon detectors with a total area of 2000 m$^2$, distributed over an area of 1 km$^2$. The observatory is placed in the Tunka Valley (50 km from Lake Baikal), at the same place where the EAS Cherenkov array Tunka-133 is located [3].

The advantage of the Cherenkov telescope as part of the complex of wide-angle timing Cherenkov stations is a possibility to obtain additional information about position of the shower axis (±10-15 m), direction to the source (±0.4°), and the primary particle energy. All these parameters are determined by the wide-angle Cherenkov stations instead of the IACT telescopes.

This allows maintaining a high level of rejection up to 0.01 for showers induced by cosmic rays at the energy of 100 TeV, even when the distance between the IACTs is up to 600 m. The sensitivity for local sources in the energy range of 30–200 TeV is expected to provide $5\sigma$ excess (or ~10 detected events) for 500 hours observation time.

2. Current status

The array contains 28 TAIGA-HiSCORE stations and a single IACT, the area of the array is 0.25 km$^2$. In 2017, 32 HiSCORE stations will be added to increase the array area to 0.6 km$^2$. The expected integral sensitivity of this array with 200 hours of observation of the source (about 2 season of operation) in the range 30–200 TeV is about $10^{-12}$ erg/(cm$^2 \times$ sec) [4]. Description of TAIGA-HiSCORE is given in [4] and in [5, 6] of these proceedings.

The Atmospheric Cherenkov telescope is of Davis-Cotton system with 34 mirrors (now only 6 of them are installed, Figure 1), 60 cm diameter each, and the focal length of 4.75 m. The camera of the IACT contains 504 photomultipliers (PMTs; up to 588 in the near future), each of them is the XP1911 PMT with 2 cm diameter photocathode. The FOV of the camera – $10^\circ x10^\circ$. The camera has modular structure with the same clusters of 28 PMTs in each (Figure 2). The basis of the readout electronics of a single cluster is a 64-channel ASIC MAROC 3. Each channel includes a preamplifier with the adjustable gain, charge sensitive amplifier, and a comparator with the adjustable threshold. The chip has a multiplexed analog output with a signal proportional to the input charge. It is also connected to a 12-bit external ADC. Signals from each PMT go to 2 channels with preamplifier gains different by a factor of 30. This results in the full dynamic range of 3000 photoelectrons (p.e.).
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Figure 1: Photos of the TAIGA-IACT telescope (left) and the camera modular structure (right).

Figure 2: Camera of TAIGA-IACT (left) and clusters of photomultipliers of the camera (right).

The number of PMT clusters in the camera is 19. Each of these clusters has its own trigger: a signal amplitude in two PMTs of the same cluster should exceed the threshold level (∼7 p.e.) within the period of 15 ns. Only the triggered clusters send information to the DAQ. The number of hit (which means ‘triggered’) clusters ranges from 1 to 19, and the distribution of this number is depicted in Figure 3 (left). After the fall from 1 to ∼10 the number of hit clusters slowly rises again, which stands for the special kind of the IACT images: a reflected scattered light originated from the snow. TAIGA-IACT sees these events because it’s the most northern IACT located in a snow covered area. The ‘snow’ events are caused by the real EAS incident outside of the IACT aperture but still registered by TAIGA-HiSCORE. They give the full light to all clusters of the camera, which results in an abnormally high number of triggered clusters (≥∼10). An example of such event is plotted in Figure 3 (right). The frequency of these snow background EAS events is relatively low (Figure 3, left) and does not disturb data taking; furthermore, installation of all 34 IACT mirrors instead of the 6 currently installed will sufficiently reduce this frequency.
3. Event reconstruction

The number of all triggered events detected by TAIGA-IAC7 varied from $\sim 10^6$ (\sim 4 hours of observation, 70 Hz, bad weather conditions) to $\sim 9.2 \times 10^6$ (\sim 8 hours of observation, 350 Hz, good weather conditions) per night. Roughly 1/20 of these triggered events were the events from the EAS, that is from $\sim 0.5 \times 10^5$ to $\sim 4.6 \times 10^5$ events per night, the rest were just the night sky background events that have occasionally passed the trigger conditions. Even smaller part of these events (from $\sim 1.2 \times 10^3$ to $\sim 10^4$ per night) were detected also by TAIGA-HiSCORE. They are denoted as ‘joint events’ below.

Before analyzing TAIGA-IAC7 images, all values of the signal amplitude in photomultipliers of the camera were transformed from ADC codes to photoelectrons. We took into account the difference between quantum efficiency of various photomultipliers as well as the difference between their sensitivity \[7\]. After that the image cleaning procedure was performed to remove the night sky background light from TAIGA-IAC7 events: amplitude cut in a pixel and amplitude cut in the next neighbor pixel were applied together with the minimal number of pixels per image (6 pixels) and minimal number of photoelectrons per image (50 p.e.) conditions.

An example of the experimental event is drawn in Figure 4. In Figure 5 examples of the joint events are presented. For these events the shower core position is determined by TAIGA-HiSCORE and projected onto the camera plane. The image major axis (Hillas formalism \[8\], black line) is in good agreement with the direction from the image to the shower core (red line).

4. Image size spectra

A very important characteristic of the IAC7 image is the so called ‘image size’, which means a total sum of all photoelectrons in the image. It’s similar to the number of photoelectrons Q measured by the non-imaging part of TAIGA, TAIGA-HiSCORE.
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The image size was calculated in experiment and simulation for both groups of events: ‘joint’ events detected not only by the IACT, but also by TAIGA-HiSCORE, and ‘all events’ detected by the IACT. All the comparisons were performed on a new simulation, which includes fast and slow shaper simulation, trigger simulation, amplitude readout simulation, 6 mounted mirrors configuration, amplitude cut on 200 p.e./pixel (as compared only with the low gain channels in the experiment), and precise characteristics of Winston cones and dimensions of the camera shadow.

In Figure 6 the spectra of the image size are presented for the comparison of the experiment and simulation. For illustration we show two Monte Carlo predictions: 3–1000 TeV and 100–1000 TeV. From the energy measurements of TAIGA-HiSCORE we conclude [9] that the joint event threshold is \( \sim 100 \) TeV; Figure 6 also demonstrates good agreement between the joint events and simulated ones with the energies greater than 100 TeV. The spectrum of all the events (red curve) in the region to the left from 100-150 p.e. represents the readout of the night sky background events, which occasionally pass the trigger in a single cluster.

Figure 4: An example of the experimental event.

Figure 5: Examples of the joint events in experiment.
5. Correlation between the Cherenkov photon density measured by TAIGA-HiSCORE and TAIGA-IACT

In Figure 7 (left) we present the comparison of the IACT image size with the prediction of this value obtained in TAIGA-HiSCORE. The prediction was taken as a result of the fit of lateral distribution function (LDF) measured by HiSCORE \cite{10} (Figure 7, right). The dependence of the measured value on its predicted value is linear with some fluctuation around the theoretical line. This result both confirms the correct functioning of the IACT and demonstrates the possibility of using the IACT as an additional hit detector in the TAIGA-HiSCORE installation.

Figure 7: Left: the image size estimation ($Q_{\text{HiSCORE}}$) based on the LDF function obtained in TAIGA-HiSCORE vs the image size in the TAIGA-IACT. The number of events is large, so the statistical errors of the points are negligible. The straight line denotes the theoretical prediction calculated with the use of the quantum efficiency and the detection area of both TAIGA-HiSCORE and TAIGA-IACT types of detector. Right: the image size estimation procedure.
6. Conclusions and future plans

The first IACT of the unique complex of installations for the study of high-energy cosmic rays is constructed and put in operation at the Tunka Astrophysical Center. It is a next important step towards construction of the TAIGA gamma-ray observatory. The first data of the IACT are obtained and analyzed, including joint events detected by both the IACT and TAIGA-HiSCORE parts of the observatory. This analysis demonstrates the good performance and high reliability of the equipment and good agreement with the Monte Carlo simulation of both TAIGA-IACT and TAIGA-HiSCORE installations.

Additional 32 stations of TAIGA-HiSCORE will be deployed in 2017, so that even prior to the winter season 2017–2018 the TAIGA configuration will include 60 wide angle stations arranged over an area of 0.6 km$^2$, as well as a single IACT. The expected integral sensitivity for 200 hours of a source observation (about 2 seasons of operation) in the range 30–200 TeV is about $10^{-12}$ erg/(cm$^2$×sec). In the next two years the number of the IACTs will be increased up to 3.

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References

[9] L. Sveshnikova et al. (TAIGA Collaboration), Search for gamma-ray emission above 50 TeV from Crab Nebula with the TAIGA detector, These proceedings.