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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 working 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 count rates and image size spectra for all events detected by the IACT and the joint events detected also by the HiSCORE array, comparing these with expectations from MC simulations.

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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 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°x10°), covering an area of 5 km^2, and 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, direction to the source, and the primary particle energy [4]. All these parameters are determined by the wide-angle Cherenkov stations instead of the IACT.

This allows maintaining a high level of rejection up to 0.01 [5] for showers induced by cosmic rays at the energy of 100 TeV, even when the distance between IACTs is up to 600 m. Below we present the current status of the telescope commissioning (with 6 mirrors out of 34) and its joint operation with 28 stations of the HiSCORE array. We focus on the analysis of the first data obtained in March 2017: trigger conditions, background cosmic ray flux, counting rates and image size spectra for all events detected by the IACT and the joint ones detected by both the IACT and the HiSCORE array, comparing these with expectations from MC simulations.

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 2017-2019, HiSCORE will have 100–120 stations to increase the area to 1 km^2. Description of TAIGA-HiSCORE is given in [5] and in [4, 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°x10°. 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.).

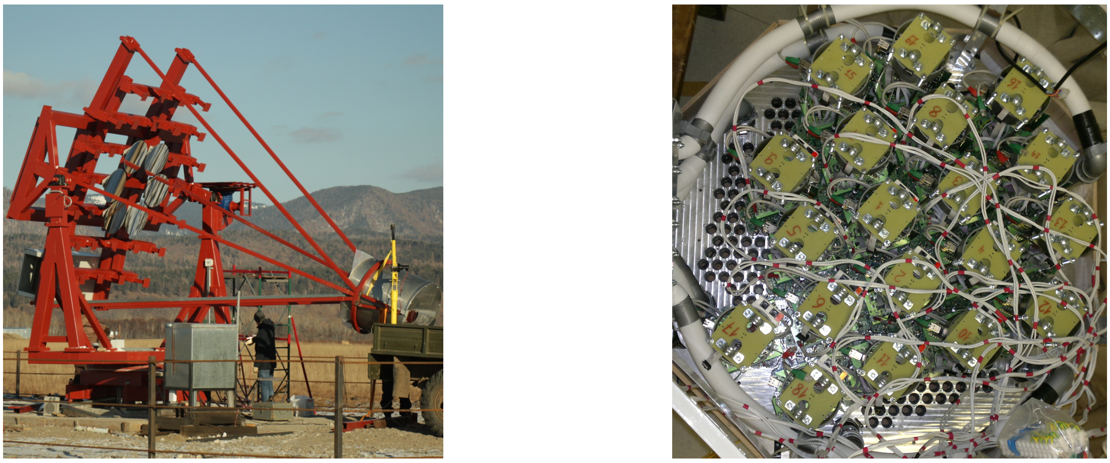


Figure 1: Photos of the TAIGA-IACT telescope (left) and the camera modular structure (right).

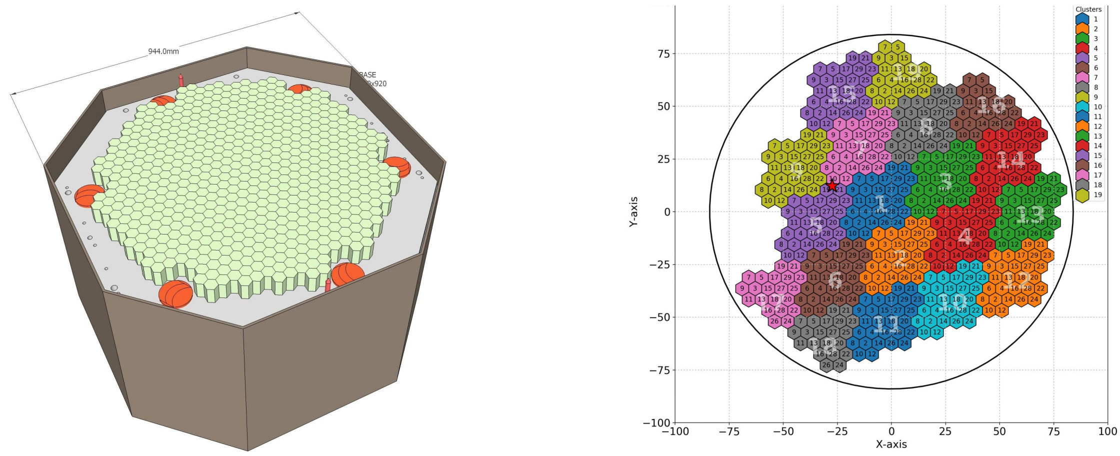
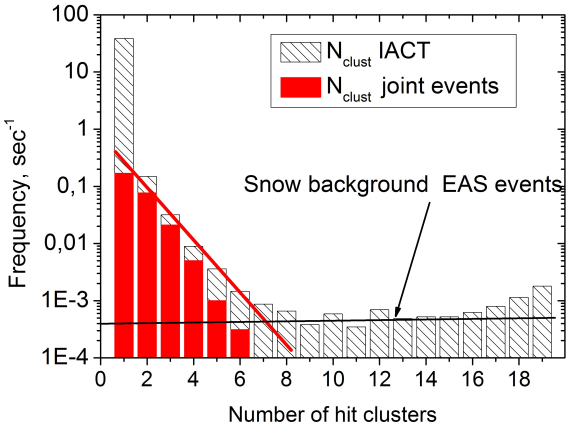


Figure 2: Camera of TAIGA-IACT (left) and clusters of photomultipliers of the camera (right).

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 ($\gtrsim$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. The red histogram of the Figure 3 left panel represents the frequency of triggered clusters for showers detected by both IACT and the HiSCORE array. As a rule, these real showers hit from 2 to 6 clusters of the chamber.



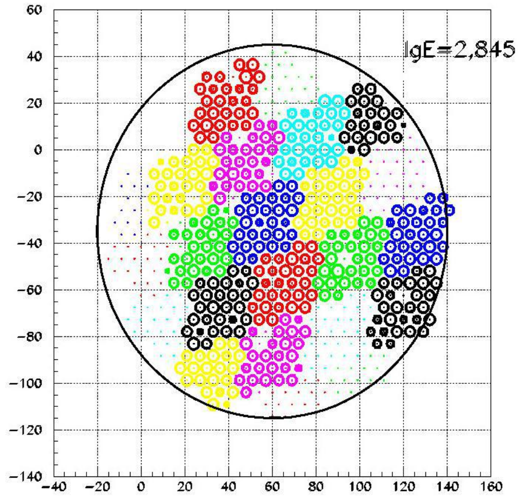


Figure 3: Number of hit clusters of the IACT camera: left panel – frequency of hit clusters during one night of observation (total 19 clusters in the camera): grey are events, detected only by IACT; red are events, detected by IACT + HiSCORE. First peak at N=1 mostly means the night sky background light events; a long tail of grey histogram (N>9) – a special class of snow background EAS events. Right panel – an example of pixel distribution for a snow background EAS event (various clusters are differentiated by color).

3. Event reconstruction

EAS count rate of the IACT is $\sim 5\times 10^5$ events per night. Part of these events ($\sim 10^4$ per night) was detected also by TAIGA-HiSCORE, they are denoted as 'joint events' below.

Before analyzing TAIGA-IACT 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-IACT 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 IACT 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.

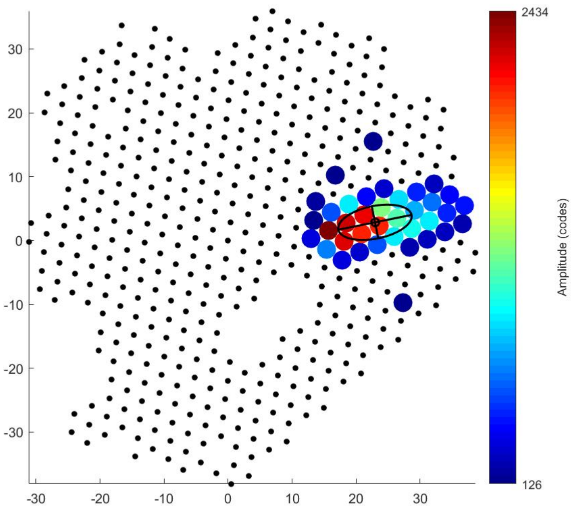


Figure 4: Example of the image of experimental event together with the Hillas ellipse and major and minor axes. Pixels above threshold are denoted by colored points, pixels below threshold – by grey points.

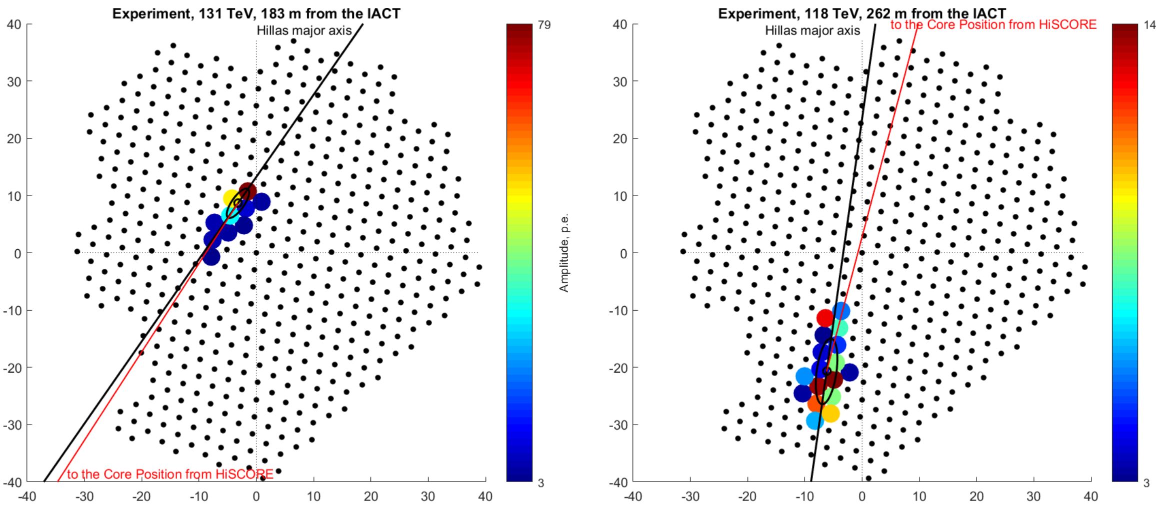


Figure 5: Two examples of joint experimental events with the Hillas ellipses. The shower axis determined by TAIGA-HiSCORE is projected onto the camera plane (red line). The image major axis (Hillas formalism [8], black line) is in good agreement with the red line.

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 image size are presented for comparison of 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 ∼100 TeV; Figure 6 also demonstrates good agreement between the joint events and simulated ones with energies greater than 100 TeV (the corresponding threshold in photoelectrons ∼300–400 p.e). The region 120–300 p.e. corresponds to the showers with energies E<100 TeV. The spectrum of all 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. The energy threshold after deployment of all 34 mirrors is expected as ∼3 TeV.

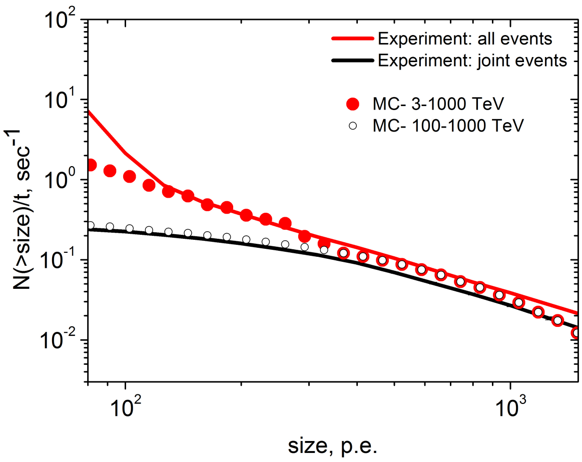


Figure 6: Image size integral spectra detected during one night by only IACT (red line), and by IACT+HiSCORE joint events (black line). Monte Carlo predictions for different energy threshold: 3–1000 TeV (red circles) and 100–1000 TeV (black circles).

5. Correlation between the Cherenkov photon density measured by TAIGA-HiSCORE and TAIGA-IACT

In Figure 7 (left) we present 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 [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.

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 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.

In 2017–2019 the number of TAIGA-HiSCORE stations will be increased up to 100–120 (area of 1km^2) and the number of IACTs will be increased up to 3. The expected integral sensitivity for 300 hours of a source observation (about 2 seasons of operation) at 100 TeV will be about 2.5×10^{-13} TeV/(cm$^2\times$sec).

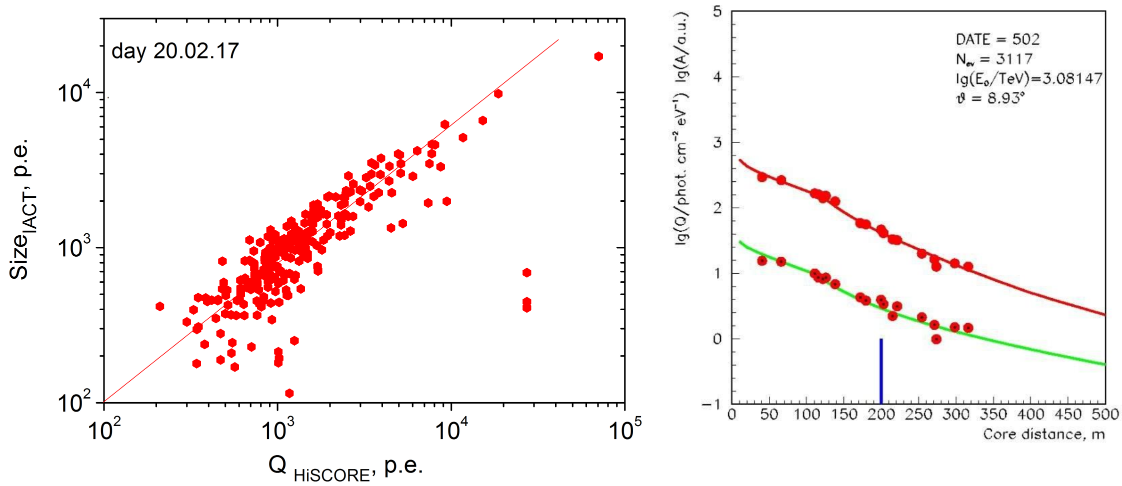


Figure 7: Left: the image size estimation (Q_{HiSCORE}) based on the LDF function obtained in TAIGA-HiSCORE vs the image size in TAIGA-IACT. The number of events is large, so the statistical errors of the points are negligible. The straight line denotes the theoretical prediction calculated with the 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.

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