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ELEMENTARY PARTICLES AND FIELDS

Experiment

The TAIGA—a Hybrid Detector Complex in Tunka Valley for Astroparticle Physics, Cosmic Ray Physics and Gamma-Ray Astronomy

I. Astapov(1), P. Bezyazeekov(2), E. Bonvech(3), A. Borodin(4), N. Budnev*(2), A. Bulan(3), D. Chernov(3), A. Chiavassa(5), A. Dyachok(2), A. Gafarov(2), A. Garmash(6),(7), V. Grebenyuk(4),(8), E. Gress(2), O. Gress(2), T. Gress(2), A. Grinyuk(4), O. Grishin(2), A. D. Ivanova(2), A. L. Ivanova(6),(2), M. Iliushin(2), N. Kalmykov(3), V. Kindin(1), S. Kiryuhin(2), R. Kokoulin(1), K. Kompaniets(1), E. Korosteleva(1), V. Kozhin(1), E. Kravchenko(6),(7), A. Kryukov(3), L. Kuzmichev(3),(2), A. Lagutin(9), M. Lavrova(4), Y. Lemeshev(2), B. Lubsandorzhiev(10),(3), N. Lubsandorzhiev(3), S. Malakhov(2), R. Mirgazov(2), R. Monkhoev(2), E. Okuneva(3), E. Osipova(3), A. Pakhorukov(2), L. Pankov(2), A. Pan(4), A. Panov(3), A. Petrukhin(1), D. Podgrudkov(3), E. Popova(3), E. Postnikov(3), V. Prosin(3), V. Ptuskin(11), A. Pushnin(2), R. Raikin(9), A. Razumov(3), G. Rubtsov(10), E. Ryabov(2), V. Samoliga(2), I. Satyshev(4), A. Silaev(3), A. Silaev (junior)(3), A. Sidorenkov(10), A. Skurikhin(3), A. Sokolov(6), L. Sveshnikova(3), V. Tabolenko(2), B. Tarashchansky(2), L. Tkachev(4),(8), A. Tanaev(2), M. Ternovoy(2), N. Ushakov(10), A. Vaidyanathan(6), P. Volchugov(4), N. Volkov(9), D. Voronin(10), A. Zagorodnikov(2), D. Zhurov(2),(12), and I. Yashin(1)

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Abstract—The physical motivations and performance of the TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) project are presented. The TAIGA observatory addresses ground-based gamma-ray astronomy at energies from a few TeV to several PeV, as well as cosmic ray physics from 100 TeV to several EeV and astroparticle physics. The pilot TAIGA-1 complex locates in the Tunka valley, ~ 50 km West from the southern tip of the lake Baikal. It includes integrated air Cherenkov TAIGA-HiSCORE array with 120 wide-angle optical stations distributed over on area 1.1 square kilometer about and three 4-m class Imaging Atmospheric Cherenkov Telescopes of the TAIGA-IACT array. The latter array has a shape of triangle with side lengths of about 300, 400 and 500 m. The integral sensitivity of the 1-km^2 TAIGA-1 detector is about 2.5×10^{-13} TeV cm^{-2} s^{-1} for detection of $E \geq 100$ TeV gamma-rays in 300 hours of source observations. The combination of the wide-angle Cherenkov array and IACTs could offer a cost effective-way to build a large (up to 10 km^2) array for very high energy gamma-ray astronomy. The reconstruction of a given EAS energy, incoming direction, and the core position, based on the TAIGA-HiSCORE data, allows one to increase the distance between the relatively expensive IACTs up to 600–800 m. These, together with the surface and underground electron/Muon detectors, will be used for selection of gamma-ray-induced EAS. Present status of the project, together with the current array description, the first experimental results and plans for the future are reported.

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(1)National Research Nuclear University MEPhI, Moscow, Russia.

(2)Irkutsk State University, Irkutsk, Russia.

(3)Skobeltsyn Nuclear Physics Research Institute, Moscow, Russia.

(4)Joint Institute for Nuclear Research, Dubna, Russia.

(5)Dipartimento di Fisica, Generale Universiteta di Torino and INFN, Turin, Italy.

(6)Novosibirsk State University, Novosibirsk, Russia.

*E-mail: `nbudnev@api.isu.ru`

(7)Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences (BINP SB RAS), Novosibirsk, Russia.

(8)Dubna State University, Dubna, Russia.

(9)Altai State University, Barnaul, Russia.

(10)Institute for Nuclear Research RAS, Moscow, Russia.

(11)IZMIRAN, Troitsk, Moscow, Russia.

(12)Irkutsk National Research Technical University, Irkutsk, Russia.

1. INTRODUCTION

The TAIGA Astrophysical complex (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) [1, 2] (Fig. 1) is intended to study the charged cosmic rays and gamma radiation in the energy range 10^{13}–10^{18} eV by detecting extensive air showers (EASs). The complex includes a unique system of hybrid detectors: three Imaging Atmospheric Cherenkov Telescopes (IACT) [3], two wide-angle Cherenkov arrays—Tunka-133 and TAIGA-HiSCORE (High Sensitivity COsmic Rays and gamma Explorer) [4, 5] with an effective area of 3 and 1 km^2 respectively, as well as two arrays for detecting charged cosmic rays—Tunka-Grande [6] and TAIGA-Muon [7].

The key idea is to combine two fundamentally different methods for detecting EAS Cherenkov radiation (imaging and non-imaging (timing)) into a single complex. Namely, the IACT telescopes are designed to register the Cherenkov image of EAS, the Tunka-133 and TAIGA-HiSCORE arrays consist of non-imaging wide-angle Cherenkov detectors. The main advantage of joint operation of IACTs and wide-angle Cherenkov arrays is possibility to separate gamma-ray events from background of charged cosmic rays according to the data of one or several IACTs using information about the energy, core position and arrival direction of the EAS, reconstructed from the data of wide-angle arrays.

The main tasks of the TAIGA observatory include solving actual problems of gamma astronomy and cosmic-ray physics:

—Study of the energy spectrum of gamma-quanta from Galactic sources and search for new sources of gamma-quanta. It is planned to reconstruct the gamma-ray spectrum from galactic sources (Crab Nebula, Dragonfly, J2227 + 610 (G106.3 + 2.7), J2031 + 415 (Cygnus Cocoon), Tycho Brahe supernova) important for understanding the origin of cosmic rays.

—Monitor the flux of gamma rays from nearby extragalactic sources. The study of the shape of the gamma-quanta spectrum with energies above 8–10 TeV from extragalactic sources will make it possible to obtain confines on the density of extragalactic background radiation (EBL), to search for “axion-like” particles.

—Search for TeV-range gamma-quanta from gamma-ray bursts and gamma-quanta correlated with high energy neutrinos.

—Search for space accelerators in which protons are accelerated to energies of 100–3000 TeV. To search for such accelerators, the features of the spectrum of charged cosmic rays in the energy range 100–3000 TeV will be studied. The proportion of protons and helium among the nuclei of charged cosmic rays will be measured.

—Study of the mass composition of cosmic rays in the region of transition from galactic to extragalactic rays.

The article is organized as follows. The second section provides a brief description of the astrophysical complex facilities. Section three presents the latest results on the study of cosmic rays. The fourth section is devoted to research on gamma astronomy. The last section describes plans for the further development of the astrophysical complex.

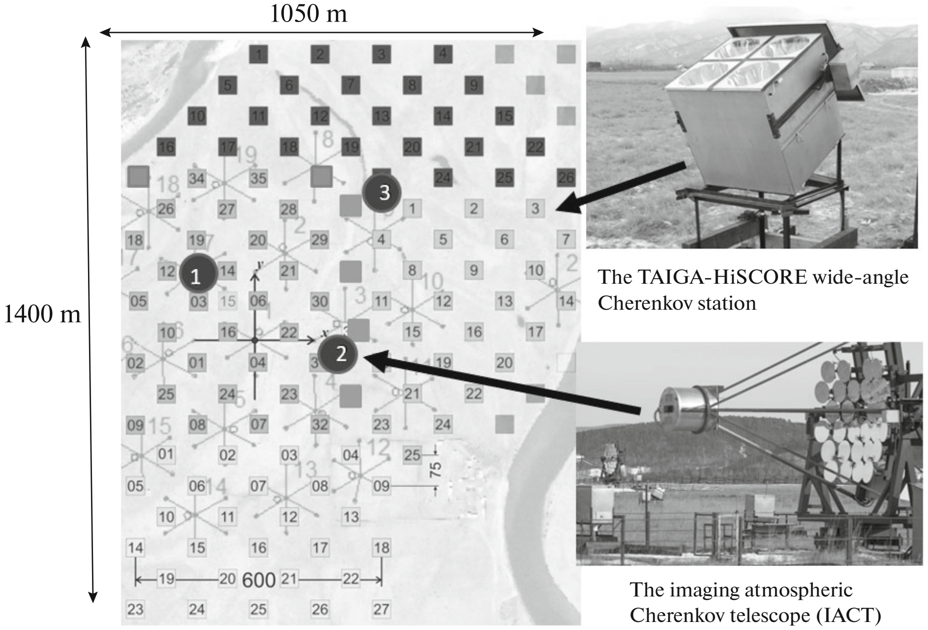
2. TAIGA ASTROPHYSICAL COMPLEX

Currently, the following arrays are operating as part of the TAIGA complex: Tunka-133, Tunka-Grande, TAIGA-HiSCORE, TAIGA-Muon, TAIGA-IACT. An overview of arrays is given in [8]. All facilities of the complex are synchronized with each other with an accuracy of 10 ns [5]. This section briefly describes only two of these facilities used for research in the field of gamma-ray astronomy—the TAIGA-HiSCORE and TAIGA-IACT.

2.1. TAIGA-HiSCORE

The TAIGA-HiSCORE array [9, 10] is a network of wide-angle optical stations for detection of EAS Cherenkov radiation. At present, the array consists of 120 stations located on an area of 1.1 km^2, the distance between stations is 106 m. The stations are grouped into 4 clusters with independent data collection centers. Each station is connected to the cluster data collection center with a fiber optic cable for data transmission and synchronization [5].

The optical station contains four photomultipliers (PMTs) with a diameter of 20 cm (ET 9352 and Hamamatsu R5912). The light-collecting area of each PMT was increased by a factor of 4 using a Winston cone with a diameter of 0.4 m and a viewing angle of 30° (solid angle 0.6 sr). The effective energy threshold of the facility, when four or more stations are triggering, is ~ 80 TeV for EAS from charged particles of cosmic rays and ~ 40 TeV for EAS from gamma quanta. The angular resolution of the facility changes from 0.4–0.5 degrees near facility to 0.1 degrees when more than 10 stations are triggered [11]. The large angular aperture of the facility and good angular resolution made it possible to start searching for astrophysical sources of nanosecond optical flares [12].



The TAIGA-HiSCORE wide-angle Cherenkov station

The imaging atmospheric Cherenkov telescope (IACT)

Fig. 1. Location of the TAIGA-HiSCORE Cherenkov stations (squares) and three IACTs (circles).

2.2. TAIGA-IACT

The TAIGA-IACT array currently includes 3 atmospheric Cherenkov telescopes (ACTs) with reconstruction of the angular distribution (image) of Cherenkov light from EASs. ACTs are the main tools for ground-based high-energy gamma-ray astronomy, which make it possible to separate gamma-quanta events from charged particles of cosmic rays.

The distances between the first and second telescopes are 300 m, between the second and third—400 m, between the first and third—500 m. Each ACT of the TAIGA-IACT has Davies–Cotton composite mirrors with an area of 10 m^2 and a focal length of 4.75 m [3].

Recording cameras of 600 PMT with photocathode diameter 2 cm each (XP1911) are installed at the focus of mirrors. The diameter of cameras is about 110 cm. The viewing angle of camera is 9.6°, the angle of view of one pixel is 0.36°, the point spread function (PSF) of the telescope is $\sim 0.07°$. Recording camera and data acquisition system is described in detail in the article [13]. This viewing angle makes it possible to detect EASs with an axis position of up to 500 m from the telescope. The energy threshold of the telescope is 2–3 TeV, depending on the zenith angle at which the gamma-ray source is visible.

At energies above 10 TeV it becomes possible to use stereoscopic approach—EASs from gamma-quanta are recorded by two or more telescopes [14]. At energies above 40 TeV, a new “hybrid” approach to the detection of gamma-quanta becomes possible—the detection of EASs both by telescopes and by the TAIGA-HiSCORE facility. The main advantage of the joint operation of the ACT and a network of wide-angle Cherenkov stations is a more efficient separation of events from gamma-quanta from the EAS background from charged cosmic rays.

3. ENERGY SPECTRUM AND MASS COMPOSITION OBTAINED BY THE TAIGA OBSERVATORY

3.1. Energy Spectrum of Cosmic Rays at Energies above 10 PeV

The study of the energy spectrum of cosmic rays at energies above 10 PeV is important for understanding the transition region from galactic to extragalactic cosmic rays. At the TAIGA astrophysical complex the spectrum in this energy range is studied using the data from the Tunka-133 and Tunka-Grande arrays. The spectrum obtained from the Tunka-133 data for 7 measurement seasons is given in [15]. One of the main results that follows from the obtained spectrum is the proof of a more complex dependence of the intensity of cosmic rays on energy than previously assumed. There are two statistically significant features besides the “classical knee” at an energy of 3 PeV in the spectrum. Namely, at an energy of 20 PeV the power law index decreases by about 0.2 and at an energy of 300 PeV the power law index again increases by about 0.3. According to repeated reconstruction of the Tunka-133 experimental data this year [16], the position of the second feature shifted to an energy of 100 PeV (Fig. 2*a*) and coincided with

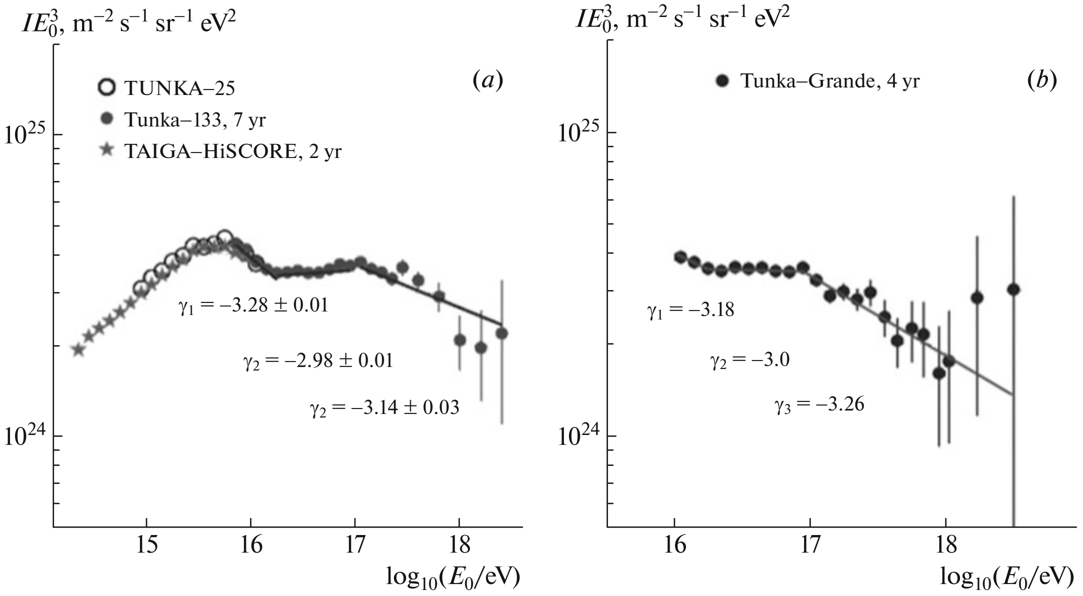


Fig. 2. Energy spectrum obtained by the Tunka-133 (*a*) and Tunka-Grande (*b*) experiments.

the result obtained by the Tunka-Grande experiment (Fig. 2*b*) [17].

A change in the power law index at an energy of 15–25 PeV is observed in most large EAS experiments ([18–20]) and can be considered reliably established. There is no astrophysical interpretation of this change in the power law index of the energy spectrum.

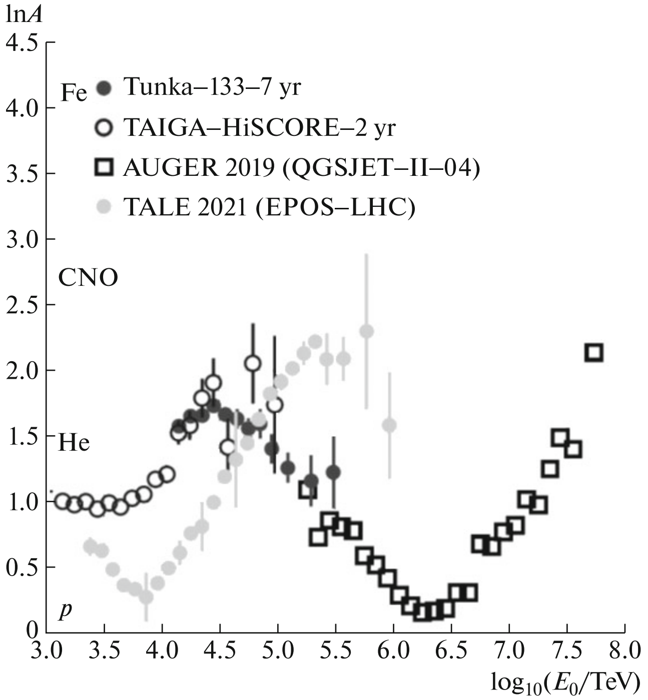


Fig. 3. Energy dependence of the mean logarithm of the atomic number ln *A*. Comparison of the results of the punka-133, TAIGA-HiSCORE, Auger [21] and TALE [22] experiments.

The steepening of the spectrum at an energy of 100 PeV can be interpreted as a “second knee” in the energy spectrum associated with the transition from galactic to extragalactic cosmic rays.

3.2. Mass Composition According to the Tunka-133 and TAIGA-HiSCORE Data

The dependence of the average mass composition of energy cosmic rays in the Cherenkov facilities is reconstructed from the energy dependence of the depth of the EAS maximum—$X_{\max}$. Figure 3 shows the energy dependence of the average value ln *A* (*A*—atomic number). Dependence of the mean value of ln *A* on energy is well extrapolated to the results of Pierre Auger Observatory at an energy of 300 PeV [21] and contradicts the results of the TALE experiment, which is much more difficult to interpret the data [22]. Our result also contradicts the results of the KASCADE-Grande [23, 24]. According to the results of KASCADE-Grande in the energy region of 100 PeV the flux of cosmic rays is dominated by iron nuclei. The feature in the spectrum of cosmic rays at this energy has a simple explanation as the limit of the acceleration of cosmic rays in galactic sources. For the light composition of cosmic rays, which follows from our results, another astrophysical explanation should be sought.

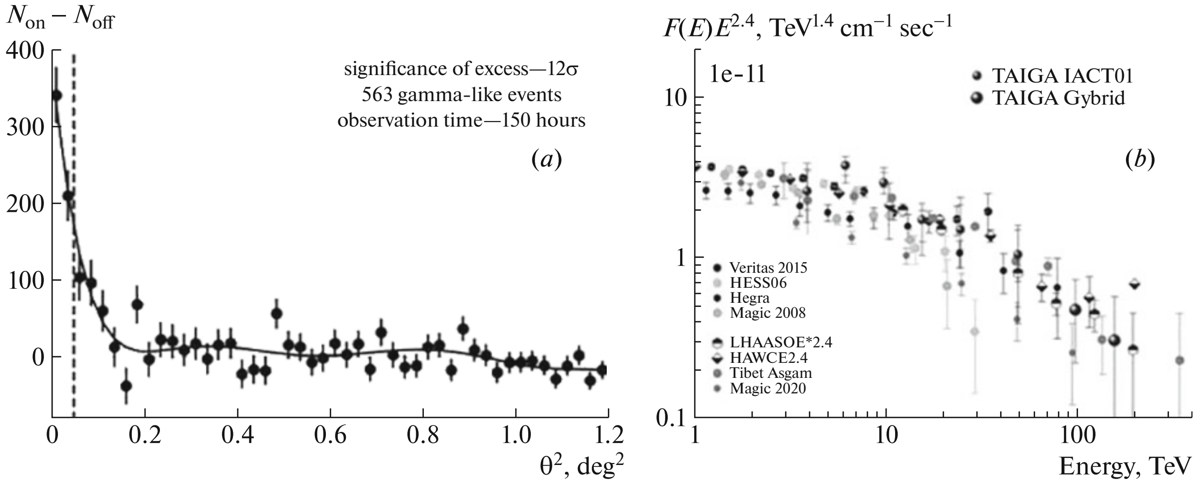


Fig. 4. (*a*) Distribution by parameter θ^2 (θ is the angle between the direction to the source and the arrival direction of this event); (*b*) The gamma-ray spectrum from the Crab Nebula reconstructed from data of the first telescope of the TAIGA experiment in comparison with the results of other observatories for 150 hours of observation. The last two points were obtained from hybrid events (IACT01 + HiSCORE).

4. GAMMA-RAY ASTRONOMY WITH THE TAIGA OBSERVATORY

The deployment of the TAIGA-HiSCORE (120 optical stations) and TAIGA-IACT (3 IACTs) facilities was completed in 2020. During the deployment of the experimental complex, the first results were obtained on the separation of gamma quanta from the Crab Nebula in mono mode (stand-alone mode) and stereo mode (from two telescopes) [25].

The observations of the Crab Nebula were performed in wobble mode [26] of pointing the telescope with 1.2° offset from the source direction. During the observations, the telescope points to (RA ± 1.2°sec(Dec), Dec) automatically switching between directions every 20 minutes.

4.1. The Energy Spectrum of Gamma-Quanta from the Crab Nebula According to the Data of the First IACT

The gamma-ray source in the Crab Nebula was observed by the first atmospheric Cherenkov telescope for 150 hours during two seasons (2019–2020 and 2020–2021), 563 events from gamma quanta in the energy range of 5–100 TeV were selected. The significance level of such several events under the background of charged cosmic rays is 12σ (Fig. 4*a*). A technique for reconstructing the energy of gamma quanta based on data from only one atmospheric telescope has been developed. When reconstructing the energy of particles, a procedure configured according to Monte Carlo simulation was used, resulting in an energy determination accuracy of about 30%, and allowing to restore the energy spectrum of events (Fig. 4*b*) [27]. The obtained spectrum of particles coincides quite well with the world data in the range from 5 to 100 TeV.

4.2. Hybrid Events During the Observation of the Crab Nebula

The total statistics of the selected hybrid events for two seasons of Crab Nebula observation is ~ 150000 (IACT01 + HiSCORE) for a time of ~ 150 hours.

The technique of such events' reconstruction is as follows. For each event, the Hillas parameters are determined, calculated as two sets of parameters "On" and "Off" for tracking the source and tracking the background. The excess is found after the suppression of the hadron background as the difference of these two samples. The spectra of gamma-like showers are plotted as the difference between the "On" and "Off" spectra. When analyzing hybrid events, parameters such as the distance to the shower axis (R_{tel}), the angle between the restored EAS direction and the direction to the source and the energy recovered by the TAIGA-HiSCORE array are additionally included.

Background suppression criteria in hybrid events allow selecting events from very long distances—up to 400 m. Therefore, in hybrid events, the effective area turns out to be orders of magnitude larger than with the operation of 1 telescope, the threshold energy for gamma-quanta turns out to be very high—about 60–80 TeV due to the high energy threshold for registering TAIGA–HiSCORE stations. The analysis used data from only a quarter of the array, with an area of 0.25 km^2. In 150 hours, 6 gamma-quanta with an energy above 100 TeV were identified (Fig. 4*b*).

Thus, according to the data of the entire TAIGA-HiSCORE array and 3 telescopes, 20–30 events with an energy above 100 TeV from the Crab Nebula can be expected for 150 hours of observation.

5. CONCLUSIONS. PLANS FOR THE FUTURE

The main scientific tasks of the complex in the field of cosmic-ray physics and gamma-ray astronomy were given in the introduction.

The immediate development of the TAIGA astrophysical complex is associated with the creation of two more atmospheric Cherenkov telescopes and a significant increase in the area of muon detectors (the TAIGA-Muon array).

One of the disadvantages of the hybrid approach in the existing version of the astrophysical complex is the significant difference between the angular aperture of Cherenkov telescopes and the aperture of the TAIGA-HiSCORE array, which leads to the possibility of observing only one source at a given time. To correct this situation, it is planned to create small image Cherenkov telescopes (SIT) with an angular aperture of 25–30 degrees and an energy threshold of 80–100 TeV. The joint operation of such telescopes and the TAIGA-HiSCORE array will increase the number of hybrid events by almost 10 times, for which it is possible to separate gamma-quanta from the background of cosmic rays events. Further development of the astrophysical complex, most likely in another place, is associated with the expansion of the TAIGA-HiSCORE array to an area 10 times larger and supplemented with small image Cherenkov telescopes.

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