Форма № 24

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA)

TAIGA project

Шифр темы: 02-2-1125-2011/2020

Направление: Физика частиц

Авторы от ОИЯИ:
A. Borodin, N. Gorbunov[*], V. Grebenyuk, A. Grinyuk, N.Kirichkov, M. Lavrova, A. Pan, A. Porelli[+], S. Porokhovoy, V. Romanov, I. Satyshev[++], Ya. Sagan, A.Sinitsa, M. Slunecka, A. Skrypnik[*], L. Tkachev, R. Wischnewski[+], D. Zhurov[**], GU+3
[*]ЛФВЭ
[+]ДЭЗИ Цойтен
[**]НИИПФ ИГУ
[++]ЛИТ

РУКОВОДИТЕЛЬ ПРОЕКТА: А.Н.БОРОДИН

ЗАМЕСТИТЕЛИ РУКОВОДИТЕЛЯ ПРОЕКТА Л.Г.Ткачев
ДАТА ПРЕДСТАВЛЕНИЯ ПРОЕКТА В НОО _____

ДАТА НТС ЛАБОРАТОРИИ 16/04/2020 (ЛЯП)

НОМЕР ДОКУМЕНТА__________

ДАТА ПРЕДСТАВЛЕНИЯ ФИЗИЧЕСКОГО ОБОСНОВАНИЯ
НА СЕМИНАРЕ ЛАБОРАТОРИИ: 06/04/2020

ДАТА ПЕРВОГО УТВЕРЖДЕНИЯ ПРОЕКТА: XX.XX.2011

Форма № 25

ЛИСТ СОГЛАСОВАНИЙ ПРОЕКТА

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA)

Шифр темы: 02-2-1125-2011/2020

Утвержден директором ОИЯИ ____________________ ____________
подпись дата

СОГЛАСОВАН

Вице-директором ОИЯИ ____________________ ____________

Гл.уч.секретарем ОИЯИ ____________________ ____________

Гл. инженером ОИЯИ ____________________ ____________

Директором Лаборатории ____________________ ____________

Гл. инженером Лаборатории ____________________ ____________

Руководителем проекта ____________________ ____________

ОДОБРЕН

ПКК по направлению ____________________ ____________

Abstract

The multimessenger astronomy is a new trend in modern astrophysics and the high energy gamma-astronomy is an important part of it. Gamma rays are the highest energy part of the electromagnetic spectrum and they are a unique tool to probe the most energetic and the most extreme processes in the Universe. There are a number of fundamental questions for Very High Energy (VHE) gamma-astronomy which presently have no answers, and first of all a question of the sources of Galactic CR with ~PeV energies.

Up to now, most data of gamma astronomy in the TeV and sub-TeV energy range have been obtained using Imaging Atmospheric Cherenkov Telescopes (IACTs), in particular with stereo systems of several such telescopes. A prototype of the gamma-ray observatory TAIGA (Tunka Advanced Instrument for cosmic-ray and Gamma-ray Astronomy) which is under construction in the Tunka Valley, targets the energy range above 30 TeV. The observatory combines several IACTs with an array of relatively cheap wide-angle non-imaging HiSCORE detectors (High Sensitivity Cosmic Origin Explorer). This allows to extend the area of the device up to several square kilometers and to suppress considerably the background from charged CR. The combination of two complementary methods of gamma-ray study allows to build a device with large area at a relatively low price. TAIGA is the first detector of this kind.

The full scale of the TAIGA observatory will cover an area of 10 km^2 and include a network of ~1000 wide field of view (0.6 sr) timing Cherenkov light HiSCORE detectors, up to 16 IACTs with shower image analysis (FOV 10×10 degrees) and muon detectors with a total sensitive area of 2000 m^2, distributed over an area of 1 km^2. A prototype of the observatory is placed in the Tunka Valley - 50 km from Lake Baikal. JINR full responsibility is the IACT's mechanics and mirror facets manufacturing. In addition, JINR team participates in shifts at the data taken in Tunka area, MC simulation and physical analysis.

During the previous 3 years the area of TAIGA-HiSCORE has increased up to 1 km^2, deploy one more IACT and 200 m^2 of new muon detectors. With such a prototype it would be possible to have a scientific program:

1. Study of high-energy edge of spectrum of the brightest galactic and extragalactic gamma-ray sources.
2. Search for Galactic Pevatrons.
3. Apply the new hybrid approach for study of CR mass composition in the range 10^{14} -10^{17} eV.
4. Study of CR anisotropy in the energy region of 100 – 3000 TeV.

TAIGA international collaboration consists of more than 70 authors from 13 scientific groups of Russia, Germany, Italy and Romania that have many years of research experience in astrophysical studies. The JINR group includes 18 scientists and engineers. Financial request is ~ 50 k$/year: 35 k$ for IACT fabrication and 15 k$ for scientific trips (Tunka IACT commission, shifts, conferences).

Introduction

The progress in understanding of the nature of high-energy CR sources in our Galaxy and in the Metagalaxy is going along of experiments registered 3 types of astroparticles: charged CR, gamma-quanta and neutrinos. For the energy range of gamma quanta above 30 TeV there are a number of fundamental questions which presently have no answers. First of all, there is the question of the sources of Galactic cosmic rays with energies of about 1 PeV, the energy region approximately adjoining the classical knee in the all-particle energy spectrum. The study of secondary gamma quanta, produced by CR in the vicinity of the source, where particles are accelerated, it is possible to clarify a mechanism of the galactic CR acceleration. In experiments H.E.S.S. [1], VERITAS [2], MAGIC [3], MILAGRO [4], HAWC [5] some sources with gamma-ray spectra extending up to several tens of TeV have been discovered. Besides a few high energy neutrino measurements with the IceCube detector are indication on the VHE gamma rays' sources which are reachable for the experimental studies.

A high energy gamma ray hitting the atmosphere starts an electromagnetic cascade of secondary e^-, e+ and photons, the Extensive Air Shower (EAS). Two separate indirect methods measure such EAS. Surface arrays of detectors measure the secondary particles that reach the ground level. Such an instrument has a close to 100% duty cycle and also a large field of view (FoV). However, their performance parameters, such as energy threshold and resolution are rather poor. In contrary, IACTs measure the Cherenkov light produced by secondary charged particles in the EAS. The observations of IACTs are mostly limited to good weather and dark nights resulting in a low duty cycle of ~10%. In addition, the FoV of IACTs is usually only a few degrees across. However, their performance parameters, such as energy and angular resolution and energy threshold allow in-depth studies of individual sources.

Up to now, the most data in the TeV and sub-TeV of gamma astronomy have been obtained using IACTs, in particular with stereo systems of several such telescopes. The prototype of the TAIGA observatory [6, 7], which is under construction in the Tunka Valley, targets the energy range of the gamma-ray above 30 TeV. The observatory combines several TAIGA-IACTs with a net of comparatively cheap wide FOV (~0.6 sr) non-imaging optical detectors TAIGA-HiSCORE [8]. This allows to extend the area of the device up to several square kilometers and to considerably suppress the background from charged CR due to the good gamma-hadron separation of IACTs (~100 at energies above 100 TeV). The combination of two complementary methods of gamma-ray separation allows to build a device with large area at a relatively low price. TAIGA is the first detector of this kind.

The full scale the TAIGA observatory will cover an area of 10 km^2 and include of ~1000 TAIGA-HiSCORE detectors, up to 16 TAIGA-IACTs with EAS image analysis (FOV ~10 degrees) and muon detectors of 2000 m^2 total sensitive area, distributed over an area 1 km^2. The advantage of IACT telescopes combined with a HiSCORE array is the possibility to use the image information about the EAS characteristics (core position, direction, energy) for better a gamma-hadron event separation. This allows, even for a distance between the IACTs up to 600 m, to maintain a level of rejection ~0.01 of hadron showers at the energy of 100 TeV. The detection sensitivity for local sources of a 10 km^2 observatory in the energy range of 30 – 200 TeV is expected to be 10^{-13} erg cm^{-2} sec^{-1} for 500 hours of observation or 10 detected events which is comparable with planned sensitivity of the main gamma-ray astronomy projects (LHAASO [9], CTA [10]) in this energy range.

Currently, TAIGA observatory prototype consists of 85 HiSCORE stations in the area of 0.7 km^2 and two IACTs**.** During of 2020 it is planned to add additional 30 HiSCORE stations and IACT with SST-1M camera based on SiPM detectors that was developed in the framework of CTA project [11]. One more IACT is expected to produce in 2021.

TAIGA will be the first installation in which telescopes are located at a distance of 300 m or more from each other and at the same time, the advantages of observing high-energy gamma-quanta in stereo mode are preserved.

With such a TAIGA prototype it would be possible not only demonstrate advantage of hybrid and stereo approach for the gamma-hadron EAS selection in multi-TeV energy range but also obtain new and interesting results when studying the high energy edge of the spectrum of galactic and extra galactic sources.

Plans in short:

2021.

MC simulation of common operation of IACT with SST-1M camera telescope and HiSCORE. Upgrade of software for IACT+HiSCORE data analysis. Study of gamma rays from the Crab nebula. Observation of the brightest galactic and extragalactic gamma-ray sources. Taking into operation the third IACT with SST-1M camera based on SiPM detectors. Production of the fourth IACT including mirror facets. Participation in the data taking in Tunka and data analysis.

2022.

Study for gammas from blazars Mkr-421, and Mrk-501 in stereo mode. Participation in the data taking in Tunka and data analysis. Taking into operation the fourth IACT.

2023.

Participation in the data taking in Tunka and data analysis. Monitoring of galactic gamma-rays' sources. Set the upper limit constants of photon-axion conversion based on the study of energy spectra from blazars Mkr421 and Mrk 501

Prepare a detailed project of the TAIGA prototype extension to the full TAIGA gamma-ray observatory.

Status of the world investigation. Motivation.

The progress in understanding the nature of sources of high-energy CR from our Galaxy and from the Metagalaxy is going along with experiments registered 3 types of particles: charged CR, gamma-quanta and neutrinos. In the widely adopted view, the Galactic component of charged CR is accelerated in shock fronts at the boundaries of expanding shells of Supernova Remnants (SNR) in the interstellar medium. The interactions of the accelerated particles with the ambient medium produce gamma-rays and neutrinos at very high energies. A breakthrough in the study of high-energy gamma radiation has been achieved with the third generation IACTs: H.E.S.S., MAGIC, VERITAS ([1,2,3]). The main competitor of IACTs for recording high-energy gamma quanta are the ground-based installations in which EAS charged particles are recorded. In this case, the separation of EAS of gamma from a background of much more numerous hadronic showers occurs by the measurement of a penetrating EAS component (muons) and by the spatial distribution of charged particles. Registration methods may vary. The main advantages of such installations are a wide viewing angle (up to 45 degrees), a full calendar time of observation, whereas for IACTs the effective dark time does not exceed 10% of the calendar. Besides, IACTs have the registration threshold is in the region of hundred GeV.

HESS (The High Energy Stereoscopic System) is an instrument of four 12m-diameter and one 28m-diameter IACTs located at 1800 m above sea level in the Khomas Highland of Namibia and has observed the Milky Way at very-high energies (VHE, E > 100 GeV) since 2004. As systematic survey of the Milky Way was completed in 2018. This survey revealed 78 VHE sources. While some of the objects can be identified as pulsar wind nebulae (PWNe), supernova remnants (SNRs) or gamma-ray binaries, the majority of the sources have no firm association with objects known from other wavelengths. The HESS focus has shifted towards more detailed studies of the morphology, spectrum and time variability of individual sources. The investigation of the high-energy end of the spectra of hard-spectra sources will help to identify PeVatrons, the sources of the Galactic CR with energies up to the knee. The results obtained from the observations of the Milky Way have the implications for future VHE gamma-ray observations.

HAWC (High-Altitude Water Cherenkov Gamma-Ray Observatory) ([12]). It is succeeded MILAGRO - a pioneer gamma observatory of ground-based installations, operated from 2000 to 2008 ([4, 5]). HAWC has 180m x 140m and is built at an altitude of 4100 m in the Sierra Negra mountains in Mexico. It consists of 300 large water tanks. Each tank is equipped with 3 peripheral and 1 central PMT. The Observatory aimed at continuous observation of gamma radiation in a wide energy range of 1–100 TeV with a very wide viewing angle about 15% of the entire sky. The gamma-hadron selection will be made by analyzing the spatial distribution of detector readings. The observation program: Galactic sources, diffuse radiation of the Galaxy, extreme Galactic accelerators, metagalactic sources, gamma bursts, etc. [13]. The differential sensitivity of the HAWC at an energy of 100 TeV over 5 years is $5 \cdot 10^{-12}$ erg / (cm^2 s) ([14]).

Tibet ASγ (the Tibet air-shower array) [15] experiment is located at 4300 m above sea level, Tibet, China, it has a wide field of view and a large effective area. It consists of the Tibet air-shower array (Tibet-AS), the air-shower core-detector array (YAC) and the underground water-Cherenkov muon-detector array (Tibet-MD). The Tibet-MD array improves its gamma-ray sensitivity in the 10-1000 TeV energy region by an order of magnitude better than any other previous existing experiments in the world. In 2019, it was announced that 24 “gamma-like” events with energy more than 100 TeV were detected, with an expected background of 5 events.

MAGIC (Major Atmospheric Gamma Imaging Cherenkov) composed of two 17-meter diameter IACTs situated 2200 meters above sea level on La Palma, Spain (28◦N, 18◦W) to detect very-high-energy gamma rays from the resulting Cherenkov air showers [3]. The two telescopes observe γ-rays above ∼ 30 GeV by imaging the short Cherenkov light flashes produced by EAS that they initiate in the upper atmosphere. The EAS are observed by both telescopes in stereoscopic mode. The integral sensitivity of the MAGIC telescopes is (0.66±0.03)% of the Crab Nebula flux for E > 220 GeV and 50 hrs of observations at zenith angles < 30◦

The Crab nebula was once considered to be a stable source until strong flares. Until now, no variability in the Crab Nebula flux has been found in the VHE regime. In 2015, MAGIC observations are performed under Very Large Zenith Angles (VLZA) and lead to a large increase in the collection area. This allows one to observe the low fluxes at TeV energies in a shorter time compared to standard observations, and to significantly increase the observable energy towards higher energies. A natural candidate for looking for > 100 TeV emission is the Crab Nebula. All three instruments MAGIC [16], HAWC [17] and Tibet AS+MD [18] array reach energies of 100 TeV without any visible cutoff (See Fig. 1).

LHAASO (The Large High Altitude Air Shower Observatory) is in Chinese Tibet at an altitude of 4300 m, work began on the creation of an installation that has to be completed in 2020 [19]. The new facility will include 18 IACTs of 32x32 SiPM cameras, 5,000 scintillation electron detectors and 1,200 muon detectors (MD) with a total area of ~40,000 m^2. Scintillation detectors of electrons and muons will be placed on an area of ~1 sq. km. Such an installation, in addition to a detailed study of the spectrum and mass composition of CR at energies up to 1 EeV, will allow to search for local sources of gamma quanta with energies above 30 TeV at a previously inaccessible sensitivity level. To search for sources of gamma quanta in the region of lower energies (~ 100 GeV), the installation will include water Cherenkov detectors with a total area of ~90000 m^2 [20]. The preliminary LHAASO results were presented at the ICRC-2019 conference.

CTA (Cherenkov Telescope Array) [10] is the most ambitious project of the 4th generation of the Cherenkov gamma telescopes, accumulating all previous experiences of the IACT telescopes with the main installation in the southern hemisphere, aimed at researching Galactic objects, and complementary to Metagalactic objects, mostly nuclei of active galaxies. The installations will consist of a dozen of 10–15 meter MST telescopes (HESS, VERITAS class) located at intervals of about 100 m, aimed at exploring the energy range of 100 GeV - 10 TeV, and a two-four 20–30 meter LST telescopes (HESS II class), designed to study the low-energy region <100 GeV. To study gamma radiation with an energy of more than 10 TeV, it is planned to deploy a lot of so-called Small Size Telescope (SST) in 300 m increments over an area of ~7 km^2.

The **TAIGA** observatory is placed in the Tunka valley (50 km from Lake Baikal) at an altitude of 675m. Its principal feature is a complementary, hybrid approach to distinguish CR events from gamma rays' ones. The directions of EAS arrival, axis position and energy restore according to the HiSCORE stations (the registration threshold of gamma-quanta EAS events is ~30 TeV) is working in conjunction with IACTs. To determine the type of particle that produced the EAS the IACT information will used mainly. Of exceptional importance is a distance between the IACTs that can be increased to 600 m, which is significantly greater than in installations with IACTs only. Thus, the amount of IACT in the TAIGA gamma-ray observatory will be approximately 10 times less per unit area than in the CTA, and the cost per square kilometer is also many times less. A comparison of existing and projected facilities shows that the sensitivity of the TAIGA observatory for detecting gamma rays with energies above 100 TeV is at the level of other new facilities.

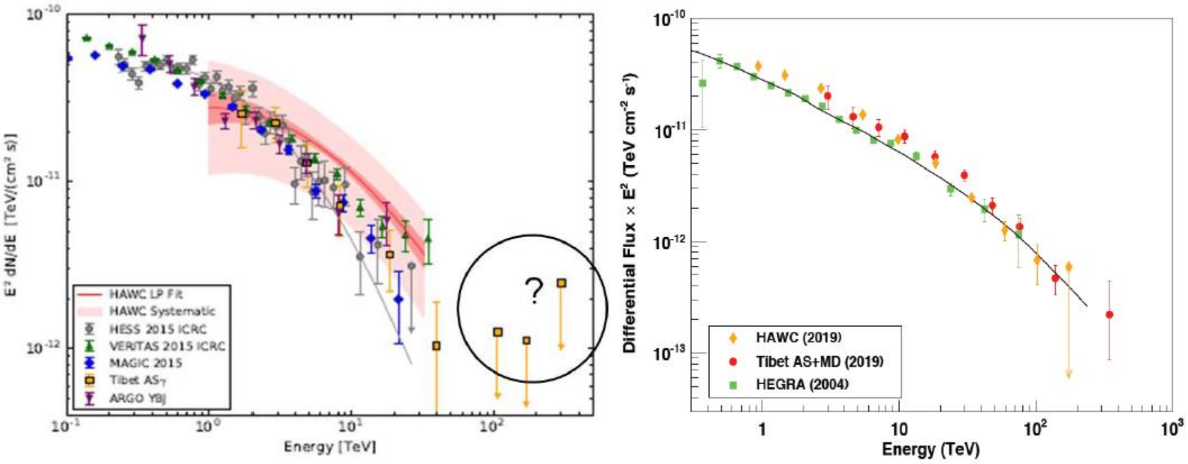


Fig. 1. Left: The Crab spectrum in 2017. Right: New measurements of the Crab spectrum.

The subject of investigation, JINR responsibility, plans and expected results.

The hybrid TAIGA observatory is under construction to study cosmic and gamma rays at energies of 10^{13}-10^{18} eV. Its principal feature is a complementary, hybrid approach to distinguish CR events from gamma rays' ones. It will incorporate timing wide-angle EAS Cherenkov detectors (TAIGA-HiSCORE) and number of TAIGA-IACTs. The first stage of TAIGA will include ~100 TAIGA-HiSCORE, distributed over an area of ~1 km^2 and 3-4 TAIGA-IACTs at a distance of 300-500 m from each other. A combined HiSCORE-IACT method will be used to select gamma-rays events. The directions of EAS arrival, axis position and energy are restored according to data of the HiSCORE stations. The registration threshold of gamma-quanta EAS is ~30 TeV. To determine the type of particle that produced the EAS the IACT information will used mainly. An exceptional importance is a distance between the IACTs that can be increased up to 600 m, which is significantly greater than for CTA detectors with IACTs only.

With such an approach a hybrid detector will be built with a large area but with a relatively small number of IACTs. Thus, per unit area, the amount of IACT in the TAIGA gamma observatory will be approximately 10 times less than in CTA and the cost per equipped square kilometer is also many times less. A comparison of the sensitivity of existing and projected facilities shows that the sensitivity of the TAIGA observatory for detecting gamma rays with energies above 100 TeV is at the level of other new facilities.

The full scale of the TAIGA observatory [6,7] will include a network of ~500 wide field of view (FOV ~0.6 sr) timing TAIGA-HiSCORE detectors, up to 16 TAIGA-IACTs with shower image analysis (FOV ~10 degrees), covering an area of 10 km^2, and muon detectors with a total sensitive area of 2000 m^2, distributed over an area of 1 km^2. This allows, even for a distance between the IACTs of up to 600 m, to maintain a level of rejection ~0.01 of showers induced by CRs at the energy of 100 TeV. The TAIGA observatory sensitivity for local sources in the energy range of 30 – 200 TeV is expected to be 10^{-13} erg cm^{-2} sec^{-1} for 500 hrs of observation or 10 detected events. Comparison of the sensitivity of existing and planned facilities shows that the sensitivity of the TAIGA observatory for registration of gamma-quanta with energies above 100 TeV is comparable with the most ambitious projects LHAASO and CTA.

The main scientific topics of the TAIGA observatory:

- Gamma-ray astronomy - one of the most intriguing questions in high-energy astroparticle physics is a search for galactic objects for accelerating of particles up to PeV-energies (the so-called Pevatrons); VHE spectra of known sources: where do they stop; absorption in Infrared Radiation (IR) and Cosmic Microwave Background (CMB); diffuse emission from the galactic plane and local supercluster.
- CR physics – the energy spectrum, mass composition and cross-section measurements from 10^{14} to 10^{18} eV.
- Particle physics - axion/photon conversion; hidden photon/photon oscillations; Lorentz invariance violation; p-air nuclei cross-section measurement; search for quark-gluon plasma phenomena.

TAIGA-IACT. The mechanical construction of the IACT was fabricated mainly at JINR on the basis of the HEGRA [21] telescope design. IACTs are of Davis-Cotton type with alt-azimuth mount, total mirror area of 9.6 m^2 (34 mirror facets each of 0.60m diameter), the driving angular accuracy is up to 0.02°. The imaging camera with weight ~ 200 kg and diameter of sensitive area of ~0.8 m [22] is based on a matrix of PMTs with Front End and DAQ electronics and is fixed at the focal length of 4.75 m in front of the mirror dish. The EAS Cherenkov light is focused on the camera by 34 mirror facets of 9.5 m curvature radius. The mirrors for the first IACT were obtained from “Galactica” (Armenia), mirrors for the second IACT are from “Media Lario Industries” (Italy).

The telescope camera consists of 560 PMTs of XP1911 type of 19 mm diameter. A FOV of a single pixel is 0.36. The FOV of the camera is 9.6^o, (each pixel has an aperture of 0.36^o). [23]. PSF = 0.07^o. The CCD-camera Prosilica GC1380 is installed at a distance of 1 m from the telescope optical axis on the mirror dish. The CCD-camera is used for checking the telescope pointing direction. It has 1360×1024 pixels resolution and 31.4◦× 23.6◦field of view. Each axis of the telescope is equipped with a Phytron hybrid stepper motor, a 17-bit shaft encoder.

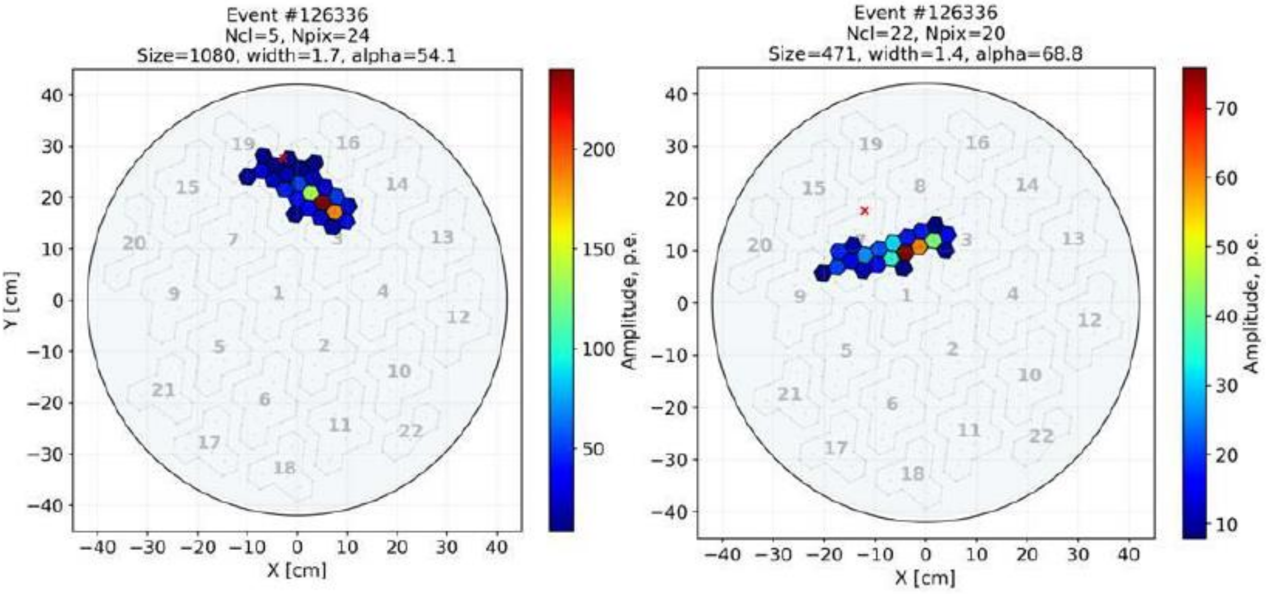
All PMTs in camera are distributed in clusters, each of 28 PMTs. The basis of the cluster electronics is a 64-channel ASIC MAROC-3. Each channel of MAROC-3 chip includes a preamplifier with adjustable gain, a charge sensitive amplifier and a comparator with adjustable threshold. The chip has a multiplexed analog output signal which is proportional to the input charge. The analog output is connected to a 12-bit external ADC. The signal from each PMT is split and fed into 2 MAROC-3 channels with a gains difference of 30. This results in a full dynamic range of 3000 photoelectrons.

The condition for the formation of a local cluster trigger is an excess of the amplitude in 2 or 3 pixels of the cluster 10 p.e. in 15 ns.

The MAROC chip for digitizing events requires a signal, named HOLD, which captures the amplitude of signal on analog output for the duration of the ADC signal digitization. Distribution of the HOLD signal to all clusters is performed by The Fast-_Hold board. The task of this board is to accept local triggers from the cluster and distribute it across all camera clusters.

Fig. 2. The both TAIGA IACTs

In December 2016 the first TAIGA-IACT was put into operation. The second one was commissioned in 2019 and put into operation in January 2020. The both TAIGA-IACTs are presented on Fig. 2 and an example of EAS event measured by both TAIGA-IACTs is presented on Fig.3.



Size = 1080 pe, Width = 0.20 °

Size = 471 pe, Width = 0.17°

Fig. 3. An example of EAS event measured by both TAIGA-ACTs

Status of JINR activity for IACT production and tests. JINR full responsibility is the IACT's mechanics manufacturing including the IACT power and motion control electronics. The mirror facets for the IACT#3 were bought in a specialized “Media Lario Industries” (Italy). In 2019, the JINR finalized a set of design drawings and produced the IACT#3 mounting for use with the SST-1M camera as part of the TAIGA observatory. A photo of the assembled IACT#3 mounting is presented in Fig.4.

Fig.4. IACT#3 mounting in assemble at JINR workshop

The IACT camera and electronics design, tests and production are a responsibility of the SINP MSU, MEPhI members of the TAIGA collaboration. JINR group participates in the production and tests of the IACT electronics.

Simultaneously JINR developed of IACT mirror facets production itself. A few mirror facets are produced and tested to complete the IACT#1 at Tunka where 5 mirror facets are absent. A comparison of the mirror facet optical parameters produced in the Media Lario company and JINR is presented in Fig.5. Spot sizes of both mirrors have comparable values and correspond well to the pixel size of the IACT camera. The main difference is the cost of the mirror production that will be much cheaper for mirrors from JINR.

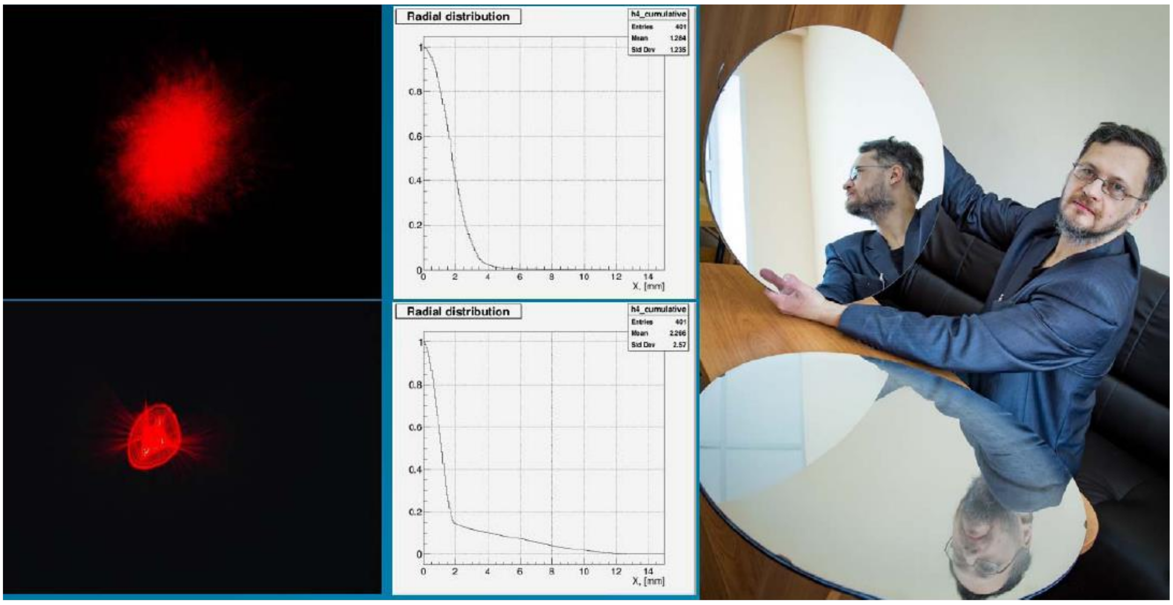


Fig.5. Left: comparison of the mirror facet optical parameters produced in the Media Lario company (top) and JINR (bottom).
Right: The first JINR facets.

Activity with SST-1M camera. The FACT collaboration [24] showed that SiPM-based cameras can be operated without damage in high night-sky background conditions. The recent progress in SiPM technology, such as increased photodetection efficiency in the UV band, improved photoelectron resolution and reduction in optical crosstalk, have allowed SiPMs to be considered as a replacement for PMTs in the next-generation Cherenkov cameras [25]. So, the next generation of Cherenkov telescope cameras feature is SiPM, which can guarantee excellent performance and allow to observe also under moonlight, increasing duty-cycle and therefore the physics reach. The SST-1M camera based on SiPM detectors was developed in the framework of CTA project [26]. The SST-1M camera (Fig.6) has been designed and produced at the University of Geneva [27] and is dedicated to the measurement of the high energy region of the gamma spectrum from 3 to 300 TeV. It consists of 1296 hexagonal SiPMs from Hammamatsu (S10943-3739(X)) connected to a frontend electronics for signal shaping and amplification. The front-end signals are recorded by the trigger and readout system DigiCam [28]. Continuous digitization with 12-bit Flash Analog to Digital Converters (FADCs) of the signal is performed at a sampling frequency of 250 MHz. A ring buffer keeps the data within the system while continuing the observations, allowing dead time free operations.

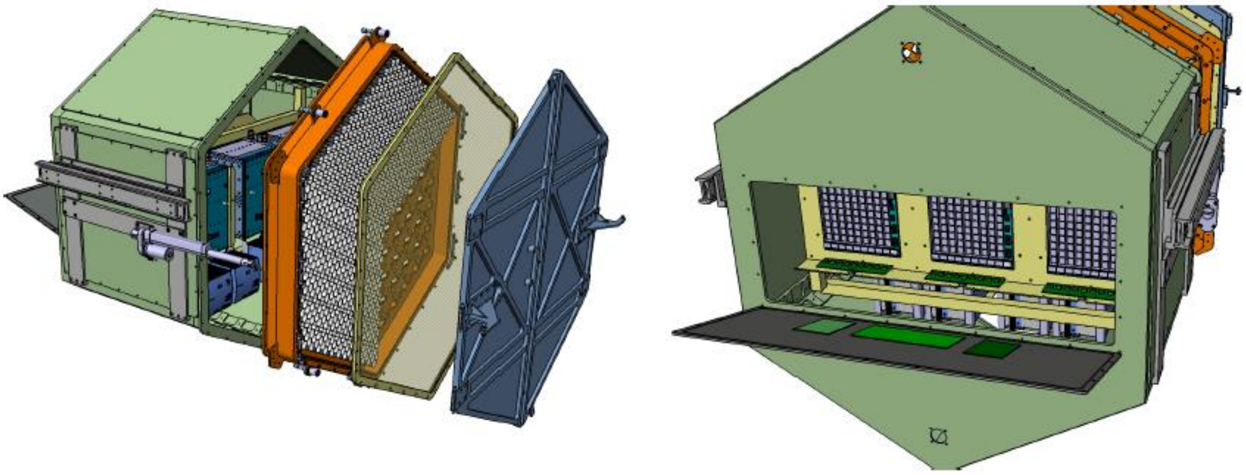


Fig. 6. Left: Exploded view of the camera. The lid doors (blue), the window frame (yellow), the PDP (orange) and the camera body (green). Right: View from the camera patch panel, which shows that one can easily access the DigiCam crates, the house keeping etc.

Presently the SST-1M camera is in University of Geneva to be completed with a sophisticated liquid cooling system due to ~2 kW electrical power inside of it. Before the delivery to Tunka, it supposes to test the camera in DESY-Zeuthen climate chamber at Siberian environmental conditions.

TAIGA-HISCORE. Currently, the TAIGA-HiSCORE array is composed of 85 optical stations distributed in a regular grid over a surface area of 0.7 km^2 with an inter-station spacing of 106 m. Each optical station contains four large area PMTs with 20 or 25 cm diameter, namely EMI ET9352KB, or Hamamatsu R5912 and R7081. Each PMT has a Winston cone with 0.4 m diameter and FOV is 0.6 sr. The anode signals of all 4 PMTs of the station are summed up. It leads to an additional lowering of the energy threshold by a factor of 2. Each station connected with the DAQ center by a fiber optic cable for data transfer and synchronization. The synchronization stability of the optical stations reaches about 0.2 ns. Precision calibration is achieved by external light sources. Reconstruction of shower parameters is performed using algorithms developed for the Tunka-133 array [29]. Arrival directions of showers are determined by the relative delay of Cherenkov light at each station. This reconstructed direction is used in the reconstruction of the EAS core. The pulse amplitude is fitted by a parameterization of the Amplitude Distance Function (ADF) [29]. The final EAS arrival direction reconstructed for a core position found assuming a curved front of the shower.

The angular resolution of the TAIGA-HiSCORE array achieves ~0.1° for high-energy events with the number of triggered stations more than 10 and ~0.4-0.5° for events with more than 4 triggered stations. The preliminary CR energy spectrum measured by the TAIGA-HiSCORE array compared with other experiments is shown in Fig. 7 [30]. The energy threshold of almost 100% efficiency of registration is about 250 TeV. Presently the extrapolation of our spectrum to the lower energies does not contradict the results of the direct experiments within their statistical errors.

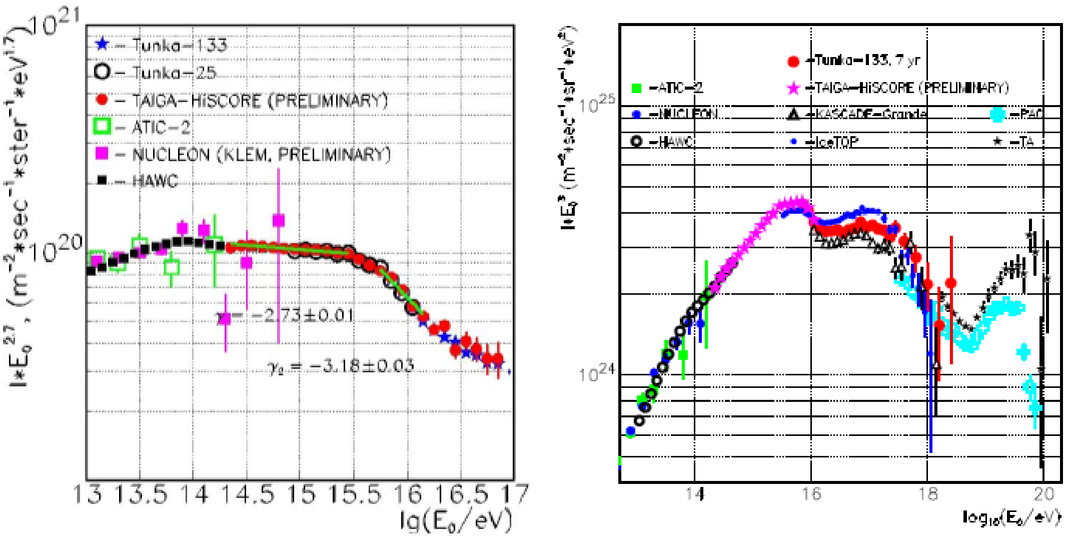


Fig. 7. Energy spectrum of primary CR measured by the TAIGA-HiSCORE array in comparison with other experiments

First results from IACTs. In season 2019-2020 observations were taken in “wobble”mode (Fomin, V. P., et al. 1994, Astroparticle Physics, 2, 137), in which the telescope pointing is offset from the source position by some angular distance. This method allows to simultaneously collect data and estimate the background. The offset distance of 1.2 ° was used, the offset direction was varied between each 20-minute run. The telescope pointing accuracy was ~ 0.0° for the corrected observations. For image analysis standard set of Hillas parameters (Width, Length, Dist …) were used (Fig. 8)

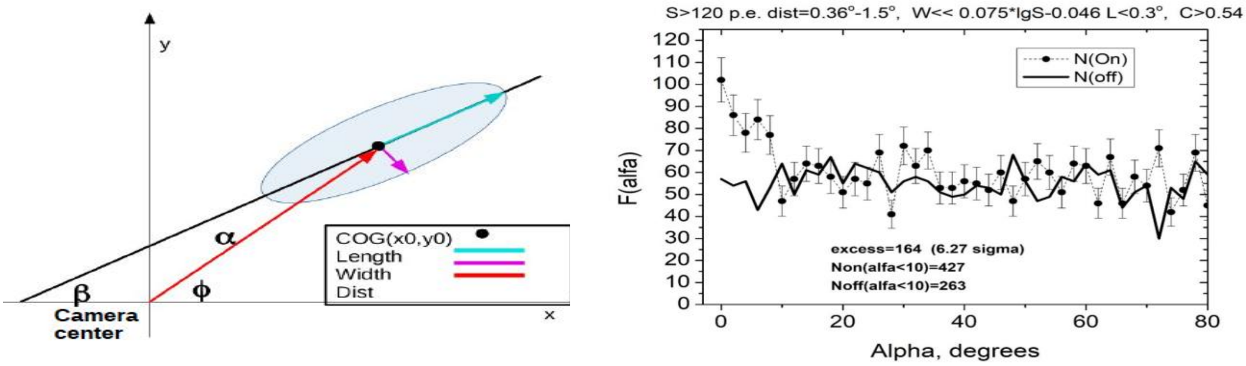


Fig.8. Left: Hillas parameters of images. Right: α-distributions of the Crab Nebula (ON, dashed line) and
the background (OFF, black) data from 46 hours observation

The Crab Nebula with the pulsar in its center is the most prominent and most studied source of TeV gamma-ray astronomy. Therefore, it is used as a standard candle for calibration of gamma - ray telescopes. After detecting signal form Crab on more than 5 standard deviation significance level (σ) telescope we can assume that the telescope passed the final commission exam.

The maximum full observation time of the source for the described HiSCORE+IACTs array is about 230 hours per year. It assumed that it is possible to reach 100 hours of observation time with good weather condition during one year.

In season 2019-2020 we observed the Crab during more than 90 hours. Data for the first period of this season (46 hours) has already been processed and the preliminary result of selecting events from is shown in Fig.7. The set of selection cuts are following: Dist: 0.4° - 1.5°, Size > 120 PE, Width < -0.046° + 0.076° × Log(Size/ 1 pe), Length <0.31°, Con2 > 0.52, α < 10°. The α-distribution of events after selection cuts for 46 hours of the Crab observation is shown of Fig. 8, for both On and Off event. Excess of events for α< 10° in near 160, which is about 6.2 σ according to the formulas of Li&Ma [36].

Such excess is in agreement to excess form MC, based on the energy spectrum of gamma-rays from the Crab, measured by HEGRA experiment ~145 events for 46 hr, In accordance to MC the threshold energy ~ 3 TeV. Such high energy threshold in compare with nearly the same size HEGRA telescope are due to the following reasons:

1. TAIGA-IACT placed on the 615 a.s.l., HEGRA- 2200 m
2. TAIGA-IACT – the most North IACT, Zenith angle events from Crab may be only larger 29°.
3. Effective area of mirrors is 6.0 m^2 (5 mirrors are not installed yet, 30% of the light is lost on slices of Winston cones). It is planned to increase effective area of mirror to 9.0 m^2. In this case the energy threshold will be decreased to 2 TeV.

The first TAIGA-IACT and TAIGA-HiSCORE hybrid results. The search for joint events recorded by the telescope and the TAIGA-HiSCORE array was carried out while tracking the Crab Nebula [37]. Fig. 9 shows an example of a joint hadron-like event detected by the telescope and TAIGA-HiSCORE. The asterisk marks the projection of the EAS core position on the plane of the telescope camera with the introduction of a scaling factor Rp (cm) / Rc (cm) = 1500, where Rp is the distance from telescope to the EAS core position and Rc is the distance between camera center and asterisk. The line on the picture directed to the EAS core. For events coming from the source to which the telescope is oriented, the line connecting the projection of the EAS axis and the center of gravity of the image should cross the center of the camera. The same event was detected by 15 stations of the TAIGA-HiSCORE array: E = 840 TeV, θ = 30.1^o, φ = 33.6^o, Rp = 134 m, the angle between direction of the shower, reconstructed by timing array, and the telescope pointing direction is 0.47^o.

.

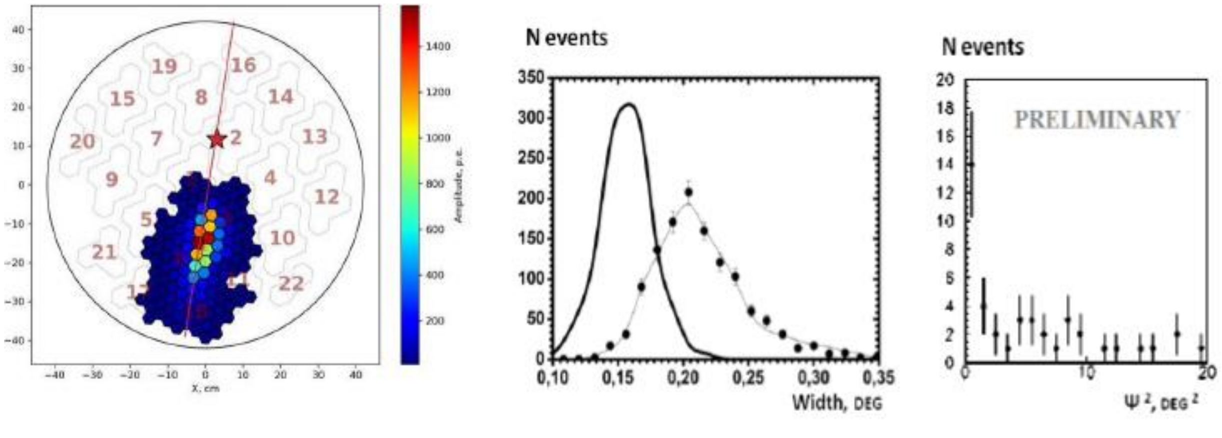


Fig. 9. Left: An example of a hadron-like joint event. Image parameters are: Size=18500 p.e., Width = 0.4°, α = 11°. Middle: Image Width distribution for joint events. Solid circles

- experiment. Thin solid line - MC (cosmic rays), thick solid line - MC (gamma quanta). Right: Ψ^2 distribution for hybrid events after cuts (preliminary results).

17,000 joint events with an image size ≥ 60 p.e. were selected. These events were detected by the first 30 stations of the TAIGA-HiSCORE array with an area of 0.25 km^2. Fig 8 shows the Width distributions for joint events with size between 1000 and 3000 p.e. The thin solid line indicates the MC simulations for a similar sample of events, obtained from experiment. The thick solid line at this figure is the Width distributions for gamma rays for the mentioned sample. Selecting 60% of gamma-events (Width < 0.17°, $\alpha < 15°$) we suppressed the hadron background by a factor of 100. After applying Width (<0.17°), α (<15°) and Dist.(< 2.5°) cuts, 42 events remain with $\Psi<4.5°$, Ψ - is the angle between direction of showers, reconstructed by TAIGA-HiSCORE and the direction of the Crab Nebula. The Ψ^2 distribution of these hybrid events after cuts is presented in Fig. 9. We should mention that for such energies multiplicity of hit HiSCORE stations is only 4-5 and angular resolution is equal to 0.4° - 0.5°. For 14 of these events, with energies between 45 and 60 TeV. These events may be considered as preliminary candidates for first gamma-like events selected by the hybrid approach.

MC simulation of common operation of TAIGA-HiSCORE and IACTS [32,33**].** The modeling of the telescope data has been done in two consecutive steps: firstly the simulation of the EAS using the program package CORSIKA [34], and secondly the calculation of the number of resulting Cherenkov photons which are reflected by the mirror of the IACT and registered by a camera of 560 PMTs in its focal plane. The input data from the non-imaging device are parameters which had been derived from the relative arrival times of the photons recorded by different detector stations: the primary energy, the direction and the position of the EAS. The direction of the primary gamma ray was fixed according to the investigated point source location, and the angle of the simulated background proton showers was varied within 0.4° around that direction, considerably wider than the actual angular resolution of the device. For each EAS in the data bank different image parameters in the IACT have been calculated, and for each configuration of these parameters we calculated the factor of background suppression:

$$Q = \varepsilon_\gamma \ / \ \sqrt{\varepsilon_{proton}}$$

where ε_γ and ε_{proton} are the fraction of events, classified as gamma-ray events from samples of true gamma-ray events and of proton-induced air showers, respectively. The standard Hillas [35] parameters used for the IACT image investigation. Including of additional parameters due to time dependence of the SiPM pixel amplitudes is in progress.

The optimum parameters from the non-imaging detectors have to be combined with the IACT parameters these are all three investigated parameters: the primary energy, the position of the shower axis, and the EAS direction. The optimum way to combine these two groups of parameters – imaging and non-imaging – is to include in the gamma-ray separation procedure.

As follows from the Q factor dependence on the core distance, we can successfully use only one single IACT for efficiently selecting gamma ray showers up to ~450 m in a hybrid installation. This situation differs from a stand-alone IACT, when the distance ~100–150 m is a limit. Therefore, the distance between two or more IACTs (if any) as parts of a hybrid installation can be significantly greater than in a stereoscopic system of IACTs. In particular, the expected location of the second IACT in TAIGA is supposed to be ~300 m apart from the first one.

Plans for 2021-2023. During these years, we plan to deploy additional ~40 optical stations. Presently the third IACT fabrication is underway at the JINR with the purpose to install it in Tunka area after the general combined mechanical tests at the JINR workshop. It is planned to install this telescope at 2020 spring in Tunka. During 2020 it is planned to deploy additional 40 stations (100 stations on 1 km^2 area) and put into operation 1 more IACT.

2021.

1. MC simulation of common operation of IACT telescope and wide-angle Tunka-HiSCORE array and optimization approach to background rejection in selection events from gamma-rays.
2. To conduct the monitoring sessions of the brightest gamma-rays source by the prototype TAIGA observatory in hybrid mode (common observation by HiSCORE and IACT). Upgrading of software for IACT+HiSCORE data analysis.
3. Study of gamma rays from the Crab Nebula in the energy range of 2 – 10 TeV (during the autonomous operation of the telescope) and prove thereby the correctness of the telescope and data-processing procedures. Observation of the brightest extragalactic gamma-ray source Mrk-421, Mrk-501.
4. Taking into operation the third IACT.
5. Production of IACT mirror facets for the fourth IACT.
6. Design, fabrication and tests of the fourth IACT mechanics in JINR workshop.

2022.

1. Comparable analysis of the TAIGA prototype data and MC simulation. Select the optimal distance between IACTs.
2. Search for gamma-rays with energy more than 30 TeV from Mkr-421 and Mrk-501 sources in hybrid mode of observation.
3. Participation in the data taking in Tunka and data analysis.
4. Taking into operation the fourth IACT.

2023.

1. Participation in the data taking in Tunka and data analysis.
2. Monitoring of galactic gamma-rays sources.
3. Search for extragalactic ELB and axion-like particles on the basis of observations of high energy edge of gamma-ray spectrum from Mkr-421.
4. Prepare a detailed project of the extension of the prototype to the full TAIGA gamma-ray observatory.

Difficulties:

1. According to the plan, TAIGA project budget is 60 k$ for 2020 for the fourth IACT fabrication. Presently (March 2020) it was available ~30%. With a budget as now it will be impossible to fulfill our plans.
2. Presently ~300 PMTs are available for fourth IACT. This is not sufficient and is unknown where will be obtained additional 300 PMTs.

The TAIGA international collaboration consists of the 14 scientific groups of Russia, Germany, Italy and Romania.

1. Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia
    - data processing and physical analysis, IACT camera fabrication, DAQ, MC-simulation
2. Institute of Applied Physics, ISU, Irkutsk, Russia
    - Tunka infrastructure, data taken, control electronics for IACTs and HiSCORE, deployment of detectors
3. Institute for Nuclear Research of RAS, Moscow, Russia

  - IACT camera fabrication, muon detectors

4. Dipartimento di Fisica Generale Universiteta di Torino and INFN, Torino, Italy
    - HiSCORE MC-simulation and data analysis
5. Max-Planck-Institute for Physics, Munich, Germany
    - Methodical question IACTs construction and calibration, data analysis, HiSCORE PMTs
6. Institut für Experimentalphysik, University of Hamburg, Germany

    IACT mirror actuator production, HiSCORE and IACT MC-simulation
7. IZMIRAN, Moscow Region, Russia
    - theoretical support
8. DESY, Zeuthen, Germany
    - SST-1M camera tests, data analysis, MC-simulation
9. National Research Nuclear University MEPhI, Moscow, Russia
    - data analysis, IACT camera fabrication , MC-simulation
10. JINR, Dubna, Russia
    - full responsibility in the design, fabrication and tests of IACTs mechanics at JINR, participation in the software development and Monte-Carlo simulation, in data taking in Tunka area and in off-line analysis. Development and production of IACT mirror facets
11. Novosibirsk State University, NSU, Novosibirsk, Russia
    - design and fabrication muon detectors
12. Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
    - design and fabrication muon detectors

13 ISS, Bucharest, Romania
  - IACT electronic components, financial contribution as JINR member-state4

14. Altai State University, Barnaul, Russia

    Tunka-Grande data processing, monitoring of weather conditions

Besides, group University of Warsaw express their interest to join TAIGA and made a financial contribution as JINR member-state.

Spokepersons: L. Kuzmichev, SINP MSU and R.Mirzoyan, MPI Munich.

Full JINR responsibility for design, fabrication and tests of the IACTs including mirror facet production. The JINR group supposes to participate in the software development and Monte-Carlo simulation, in data taking in Tunka area and in off-line analysis. JINR responsibility for HiSCORE and muon detectors are limited by assistance with customs problems.

List of the TAIGA project participants

Name	employment	involvment	PhD	Age
1. A.Borodin	senior scientist	100%	yes	>40
2. N.Gorbunov	head of sector	10%	yes	>40
3. V. Grebenyuk	senior scientist	70%	yes	>40
4. A. Grinyuk	engineer	50%	in prep	<40
5. N.Kirichkov	designer	10%	no	>40
6. M. Lavrova	junior scientist	50%	in prep	<40
7. A.Pan	engineer	50%	no	<40
8. A.Porelli[*]	senior scientist	100%	yes	<40
9. S. Porokhovoy	engineer	20%	no	>40
10. V.Romanov	designer	10%	no	>40
11. Ya.Sagan	graduated student	100%	in prep	<40
12. I.Satyshev	junior scientist	50%	no	<40
13. A.Sinitsa	designer	100%	no	<40

14. M. Slunecka	senior scientist	10%	yes	>40
15. A. Skrypnik	engineer	50%	no	>40
16. L. Tkachev	head of sector	80%	yes	>40
17. R,Wischnewski**	head of group	100%	yes	>40
18. D.Zhurov***	junior scientist	100%	in prep	<40

---

* 5% pluralistically
** 20% pluralistically
*** 40% pluralistically

Presentation at TAIGA collaboration meetings:

A.Borodin, V. Grebenyuk, A. Grinyuk, M. Lavrova, A.Porelli, I.Satyshev, Ya.Sagan, L. Tkachev, R,Wischnewski, D.Zhurov

Presentation of TAIGA at conferences:

A.Borodin, A. Grinyuk, A.Porelli, Ya.Sagan, L. Tkachev, R,Wischnewski, D.Zhurov

Bibliography

1. F.Aharonian (HESS Collaboration)//Astroparticle Physics 34(2011) 738-747
2. V.Acciari (VERITAS Collaboaration) Ap.J Letters 730 (2011) L20
3. Albert et al (MAGIC)// Astrophys.J.639:761-765,2006
4. Abdo A.A. et al.,(Milagro) 2007, ApJ 664, L91
5. A.Abdo et al. (Milagro)//arxiV: 1403.0161
6. N. Budnev et al. (TAIGA Collaboration), Jour.Phys: Conf. Series **718** 052006 (2016)
7. Budnev N. et al., (TAIGA Collaboration), NIMA **845**, 384 (2017)
8. Tluczykont, D. Hampf, D. Horns, L.Kuzmichev et al. Astropart. Phys., 56:42, 2014.
9. G.Di.Sciascio (LHAASO collaboration) //arXiv: 1602.07600
10. B.S.Acharya et al. (CTA collaboration) Astroparticle Physics 43 (2013) 3-18;
11. Schioppa E.J. et al. [CTA SST-1M Project Collaboration] // arXiv:1508.06453.
12. G.Sinnis. Nucl.Instrum.Meth.A623:410-412,2010
13. Home pager of HAWC: www.hawc-observatory.org
14. HAWC collaboration. Astroparticle Physics 50-52(2013) 26-32
15. Tibet ASγ (the Tibet air-shower array) [15]
16. M. Peresano, R. Mirzoyan, I. Vovk, P. Temnikov et al. for the MAGIC Collaboration, PoS(ICRC2019)759
17. K. Malone for the HAWC Collaboration PoS(ICRC2019)734
18. K. Kawata for Tibet AS gamma Collaboration, PoS(ICRC2019)712
19. Q.An et al et// Nucl.Instrum.Meth.A644:11-17,2011
20. G.Di.Sciascio (LHAASO collaboration) //arXiv: 1602.07600
21. R. Mirzoyan et al., Nuclear Instr. And methods A351 (1994) 513-526. DOI: 10.1016/0168-9002(94)91381-1.
22. I.I. Yashin et al. (TAIGA Coll.), Journal of Physics: Conference Series 675 (2016) 032037.
23. I.I. Yashin et al. (TAIGA Coll.), PoS(ICRC2015)986.
24. H. Anderhub et al., JINST 8 (2013) P06008 [arXiv:1304.1710].
25. A. Nepomuk Otte, D. Garcia, T. Nguyen and D. Purushotham, Nucl. Instrum. Meth. A846 (2017) 106 [arXiv:1606.05186].
26. M. Heller et al., PoS(ICRC2019)694 (2019) .
27. J. A. Aguilar et al., Nucl. Instrum. Meth. A830 (2016) 219.
28. P. Rajda et al., PoS(ICRC2015)931 (2015) [arXiv:1508.06082].
29. V.Prosin et al. (Tunka Collaboration) NIM A 756, 94 (2014)
30. N.Lubsandorzhiev et al., PoS(ICRC2019)729.
31. Y. Sagan et al., PoS(ICRC2019)776

32. E.B. Postnikov et al. Bulletin of the Russian Academy of Sciences: Physics, 2017, Vol. 81, No. 4, pp. 428-430
33. E.B. Postnikov, A.A,Grinyuk et al. Proceedings of ISVHECRI-2016
34. Heck D., Knapp J., et al. // Report FZKA 6019. Forschungszent. Karlsruhe. 1998.
35. Hillas A.M. // Proc. 19nd ICRC. La Jolla. NASA Conf. Publ., 1985. V. 3. P. 445.
36. Li, T.-P., & Ma, Y.-Q. 1983, ApJ, 272, L317.
37. L.Kuzmichev et al., NIM A 952 (2020) 161830.

References concerning the TAIGA project

1. A. Abramowski et al. (HESS Colaboration), Nature **531**, 476 (2016)
2. V. Acciari et al. (Veritas Collaboration), Astrophys. J. **730**, L20 (2011)
3. S. Ansoldi et al. (MAGIC Collaboration), Astrn.Astrophys. **585** A133 (2016)
4. Abdo, A.A. et al.,(Milagro) 2007, ApJ 664, L91
5. G.Sinnis. NIMA 623:410-412,2010, A,Aveysekara et al. arXiv:1701.01778
6. N. Budnev et al. (TAIGA Collaboration), Jour.Phys: Conf. Series **718** 052006 (2016)
7. Budnev N. et al., (TAIGA Collaboration), NIMA **845**, 384 (2017)
8. Tluczykont, D. Hampf, D. Horns, L.Kuzmichev et al. Astropart. Phys., 56:42, 2014.
9. B. S. Acharya, et al.(CTA Collaboration). Astropart. Phys., 43:3–18,2013.
10. S. Cui, Y. Liu, Y. Liu, and X. Ma. Astropart. Phys., 54:86 – 92, 2014
11. http://tevcat.uchicaho.edu/
12. M. Ackermann et al (Fermi Collaboration). Science, 339:807–811, 2013
13. G. Morlino, E. Amato, and P. Blasi. MNRAS, 392:240–250, 2009
14. S. Gabici and F. A. Aharonian. Astrophys Jour. Letters, 665:L131, Aug. 2007.
15. M. Tluczykont, M. Br ¨uckner, N. Budnev, et al.Journal of Physics: Conference Series, 632:012042, 2015.
16. P. Baillon et al (THEMISTOCLE Collaboration,). Astroparticle Ph, 1:341, Dec. 1993.

17. A. Karle, M. Merck, R. Plaga, et al. Astroparticle Physics, 3:321, Aug. 1995.
18. Budnev N. et al.// Tunka-25 Air Shower Cherenkov array v.50, c. 18-25 (2013)
19. S. F. Berezhnev, N. M. Budnev, et al. NIMA, 692:98, 2012
20. V.Prosin et al. (Tunka Collaboration) NIMA 756, 94 (2014)
21. I.Yashin et al (TAIGA Collaboration), ICPPA-2015, J. of Physics: Conference Series **675**, 032037 (2015)
22. E.B. Postnikov, A.A,Grinyuk et al. Bulletin of the Russian Academy of Sciences: Physics, 2017, Vol. 81, No. 4, pp. 428-430
23. E.B. Postnikov, A.A,Grinyuk et al. to published in proc. of ISVHECRI-2016
24. Heck D., Knapp J., et al. // Report FZKA 6019. Forschungszent. Karlsruhe. 1998.
25. Hillas A.M. // Proc. 19nd ICRC. La Jolla. NASA Conf. Publ., 1985. V. 3. P. 445.
26. L.Kuzmichev et al.(TAIGA Collaboration) to published in proc. of ISVHECRI-2016
27. L.Tkachev et al., The Proceedings of UHECR2016, T03002-001

Form № 29

Expenditure for project (K$)

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA)

Expense items	Total	2021	2022	2023
Direct expenditure				
1. LNP Design bureau (hours)	1000	800	100	100
2. LNP Workshop (hours)	1400	800	300	300
3. NPO “Atom” (hours)	30	30		
4. Materials	60	40	10	10
5. Equipment	60	40	10	10
6. Research work (contracts)	15	5	5	5

7. Business trips, including: - to states outsides rouble zone - to states insides rouble zone	30 24	10 8	10 8	10 8
Total direct expenditure	189.0	103	43	43

Project leader	A.Borodin
LNP Director	V.Bednyakov
Leading economist engineer	G.Usova

Form № 26

Proposed time-schedule and necessary resources for implementation of project (k$)

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA)

Parts and systems of set-up resources and sources o financial	Costs of parts of set-up. Required financial support

support		2021	2022	2023
LNP Design. Bureau, hours LNP Workshop, hours NPO “Atom”, hours	1000 1400 30	800 800 30	100 300 0	100 300 0
Project total	189.0	103	43	43
JINR budget	189.0	103.0	43.0	43.0
Extra-budgetary: (RSF grant, Poland)	200.0	100.0	100.0	0.0

Project leader	A.Borodin
LNP Director	V.Bednyakov
Leading economist engineer	G.Usova

Форма № 26

Предлагаемый план-график и необходимые ресурсы для осуществления проекта ТАЙГА

Наименование узлов и систем установки, ресурсов, источников финансирования	Стоимость узлов установки	Предложения Лабораторий по распределению финансировани и ресурсов.

			(тыс. долл.) Потребности в ресурсах	2021	2022	2023
Необходимые Ресурсы	Нормо-часы	КБ ЛЯП	1000	800	100	100
		НПО АТОМ	30	30	0	0
		ООЭП ЛЯП	1400	800	300	300
Источники финансирования	Бюджет	Затраты из бюджета	189.0	103.0	43.0	43.0
	Внебюджетные средства	грант РФ Грант Польша Грант РНФ	200.0	100.0	100.0	0.0
	ИТОГО		389.0	203.0	143.0	43.0

Руководитель проекта	А.Н.Бородин
Директор ЛЯП	В.А.Бедняков
Ведущий инженер-экономист Лаборатории	Г.А. Усова