Nuclear Inst. and Methods in Physics Research, A 1039 (2022) 167047

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

TAIGA—A hybrid array for high energy gamma-ray astronomy and cosmic-ray physics

N. Budnev [b,*], I. Astapov [f], P. Bezyazeekov [b], E. Bonvech [a], A. Borodin [g], A. Bulan [a], A. Chiavassa [d], D. Chernov [a], A. Dyachok [b], A. Gafarov [b], A. Garmash [k,i], V. Grebenyuk [g,h], O. Gress [b], E. Gress [b], T. Gress [b], A. Grinyuk [g], O. Grishin [b], A.D. Ivanova [b], A.L. Ivanova [i,b], N. Kalmykov [a], V. Kindin [f], S. Kiryuhin [b], R. Kokoulin [f], K. Komponiets [f], E. Korosteleva [a], V. Kozhin [a], E. Kravchenko [i,k], A. Kryukov [a], L. Kuzmichev [a], A. Lagutin [j], M. Lavrova [g], Y. Lemeshev [b], B. Lubsandorzhiev [c], N. Lubsandorzhiev [a], A. Lukanov [c], D. Lukyantsev [b], S. Malakhov [b], R. Mirgazov [b], R. Monkhoev [b], E. Okuneva [f], E. Osipova [a], A. Pakhorukov [b], A. Pan [g], L. Panasenko [k], L. Pankov [b], A.D. Panov [a], A. Petrukhin [f], I. Poddubny [b], D. Podgrudkov [a], V. Poleschuk [b], V. Ponomareva [b], E. Popova [a], E. Postnikov [a], V. Prosin [a], V. Ptuskin [e], A. Pushnin [b], R. Raikin [j], A. Razumov [a], G. Rubtsov [c], E. Ryabov [b], Y. Sagan [g,h], V. Samoliga [b], A. Silaev [a], A. Silaev Junior [a], A. Sidorenkov [c], A. Skurikhin [a], A. Sokolov [i,k], L. Sveshnikova [a], V. Tabolenko [b], A. Tanaev [b], B. Tarashchansky [b], M.Y. Ternovoy [b], L. Tkachev [g], R. Togoo [l], N. Ushakov [c], A. Vaidyanathan [k], P. Volchugov [a], N. Volkov [j], D. Voronin [c], A. Zagorodnikov [b], A. Zhaglova [b], D. Zhurov [b,m], I. Yashin [f]

[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, 1(2), Leninskie Gory, GSP-1, Moscow, 119991, Russia*
[b] *Applied Physics Institute of Irkutsk State University, 20 Blvd. Gagarina Irkutsk, 664003, Russia*
[c] *Institute for Nuclear Research of the RAS, Moscow, 27 Physichenskaya str., Troytsk, Moscow, 142190, Russia*
[d] *Dipartimento di Fisica Generale Universiteta di Torino and INFN, Via P. Giuria 1, 10125 Turin, Italy*
[e] *Puskov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the RAS, Troitsk, 142191, Russia*
[f] *National Research Nuclear University MEPhI, Kashirskoe Highway, 31. Moscow, 115409, Russia*
[g] *Joint Institute for Nuclear Research, Dubna, Joliot-Curie, 6, Moscow Region, 141980, Russia*
[h] *DUBNA University, Universitetskaya str., 19, Dubna, Moscow region, 141980, Russia*
[i] *Budker Institute of Nuclear Physics SB RAS, 11 akademika Lavrentieva prospect, Novosibirsk, 630090, Russia*
[j] *Altai State University, Prospect Lenina, 61. Barnaul, 656049, Russia*
[k] *Novosibirsk State University, 1 Pirogova str., Novosibirsk, 630090, Russia*
[l] *Institute of Physics and Technology Mongolian Academy of Sciences, Ulaanbaatar, Mongolia*
[m] *Irkutsk National Research Technical University, lermontov str., 83, Irkutsk, 664074, Russia*

A R T I C L E I N F O

Keywords:
Cosmic ray
Gamma astronomy
Timing TAIGA-HiSCORE array
Imaging TAIGA-IACT array

A B S T R A C T

The concept of the TAIGA experiment is to combine wide-angle timing and imaging Cherenkov telescopes as well as electron and muon detectors. The TAIGA facility aims at gamma-ray astrophysics at energies from a few TeV to several PeV and cosmic-ray physics from 100 TeV to several EeV but also pursues searches for astrophysical nanosecond transients, axion-like particles, Lorentz invariance violation and other unexpected manifestations of New Physics. TAIGA-1, a hybrid detector complex with an area of 1 km^2, operating since 2021 in the Tunka valley, 50 km to the West from the southernmost tip of lake Baikal, and the plans for its upgrade are presented.

1. Introduction

In recent years, the multi-TeV window in gamma-ray astronomy has been opening up. Imaging Atmospheric Cherenkov Telescope (IACT) arrays have discovered more than 200 sources with gamma-ray energy spectra extending to 1 TeV. Over the past three years, a breakthrough in the range of gamma-ray energies above 100 TeV has been made by the high-altitude installations Tibet air shower array [1] and LHAASO [2].

* Corresponding author.
E-mail address: nbudnev@api.isu.ru (N. Budnev).

https://doi.org/10.1016/j.nima.2022.167047
Received 27 May 2022; Accepted 21 June 2022
Available online 24 June 2022

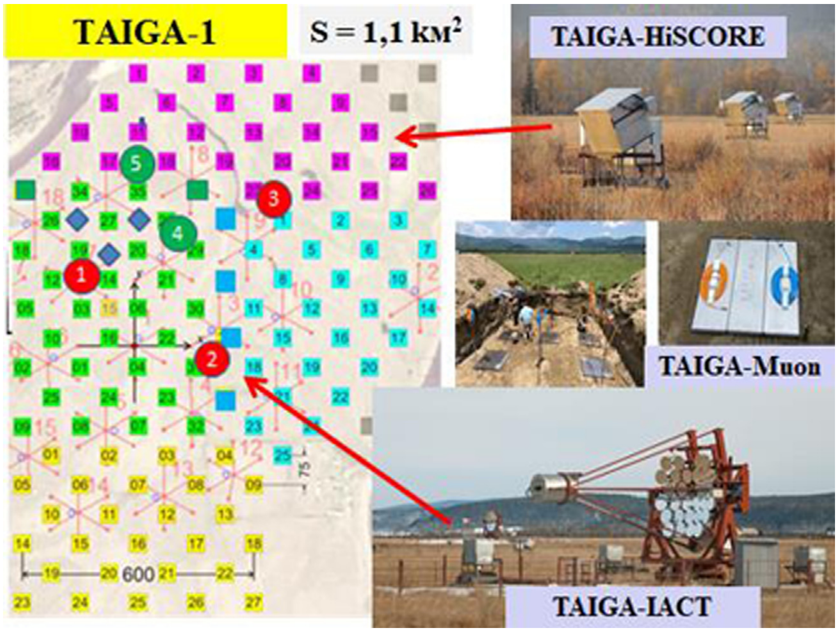

Fig. 1. Layout of the TAIGA-1 hybrid complex. Squares: wide-angle Cherenkov stations of TAIGA-HiSCORE array. Red circles: IACTs in operation, green circles: IACTs that will be deployed by 2023.

A new approach to the studies of high energy gamma rays is being developed within the TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) installation with a system of jointly working wide-angle timing installations (TAIGA-HiSCORE) and imaging Cherenkov telescopes (TAIGA-IACT) ([3]. The joint operation of such types of arrays will permit us to use for gamma/hadron separation a combination of data processing techniques generally used in the analysis of both imaging and non-imaging (timing) installations. The main advantage of the operation of the IACTs in the network of wide-angle Cherenkov stations is a more efficient gamma/hadron separation. Information about the parameters of the EAS image is supplemented by the parameters of the EAS (axis position, direction of arrival of the EAS, energy), which are well reconstructed by TAIGA-HiSCORE. Based on a this experimental approach we plan to construct a large area, up to 10 km^2, aiming at gamma-ray astrophysics at energies from 50 TeV to several PeV, cosmic ray physics from 10^{14} to 10^{18} eV and several other topics.

2. The TAIGA-1 hybrid complex

In 2022, we completed the deployment and commissioning of the TAIGA-1 hybrid complex (Fig. 1) in the Tunka valley, about 50 km from lake Baikal in Siberia. It consists of 120 TAIGA-HiSCORE wide-angle Cherenkov stations, three 4-m class Imaging Atmospheric Cherenkov Telescopes (IACT) and 250 m^2 of scintillation particle detectors.

2.1. The HiSCORE timing array

The TAIGA-HiSCORE Cherenkov stations are distributed with a spacing of 106 m over an area of about 1.1 km^2 and are grouped in 4 clusters of approximately 30 detectors each. The TAIGA-HiSCORE Cherenkov stations contain 4 PMTs with a photocathode of 20 to 25 cm diameter, EMI ET9352KB or Hamamatsu R5912 and R7081. Six-stage dividers are used to operate the PMTs in conditions of high light background. The PMT has a nominal gain of 10^4 at 1.2–1.4 kV supply voltage. The light collecting area of each PMT is increased by a factor of four by means of Winston cones with a half opening angle of 30° covering a field of view of 0.6 sr. The total light collection area of one station is 0.5 m^2. Signals from the PMT anodes and intermediate dynodes are digitized at a sampling rate of 0.5 ns with the aid of an eight-channel module based on the DRS-4 chip. A local trigger of a station is formed as soon as the amplitude of the analog sum of signals from the PMT anodes exceeds a preset threshold level of about 200 photoelectrons (ph.e.). The counting rate in the local triggers of a station is about 10 to 20 Hz. Each station is connected to its DAQ Centre via optical fiber for data transfer and timing synchronization. The accuracy of the timing synchronization is of the order of 0.2 ns relative time jitter between any two TAIGA-HiSCORE stations [4].

The effective energy threshold of the installation, when four or more stations have triggered, is ∼80 TeV for EAS from charged cosmic ray particles and ∼40 TeV for EAS from gamma quanta. The angular resolution of the installation varies from 0.4–0.5 degrees near the installation threshold to 0.15 degrees when more than 10 stations have triggered.

2.2. TAIGA-IACT

At present three IACTs of the TAIGA-IACT array have been installed at the vertices of a triangle with sides of 300 m, 400 m and 500 m inside the TAIGA-HiSCORE installation (Fig. 1). Each telescopes has a composite reflector of Davis-Cotton design about 10 m^2 in area. It is formed by 34 glass mirrors with a focal length of 4.75 m. The telescopes have alt-azimuth mounts, each of them is equipped with a Phytron hybrid stepper motor, a 17-bit shaft encoder and limit switches connected to the PhyMOTION control unit. The control unit supports a micro-step mode that is set to 1/20 of the nominal value to perform smooth tracking of a source. The telescope's absolute pointing position is determined by encoders using a pointing model and then corrected by a CCD camera to achieve a better accuracy of 0.02 degrees. It is also verified using PMT currents during special test runs by scanning bright stars [5].

2.2.1. The cameras of the TAIGA-IACT

The camera is equipped with 600 XP1911 PMTs (diameter 19 mm). All PMTs are grouped in 22 clusters with 28 PMTs each. The clusters are mounted on a carrying duraluminum plate. Winston cones are fastened on the other side of the plate whereby the photocathode area is increased by a factor of 3.5. The camera FoV is equal to 9.6° (0.36° per pixel). At a nominal operating gain of 10^5, the current of the PMT is 0.5-2 μA. At a current of 35 μA (the appearance of a bright star in

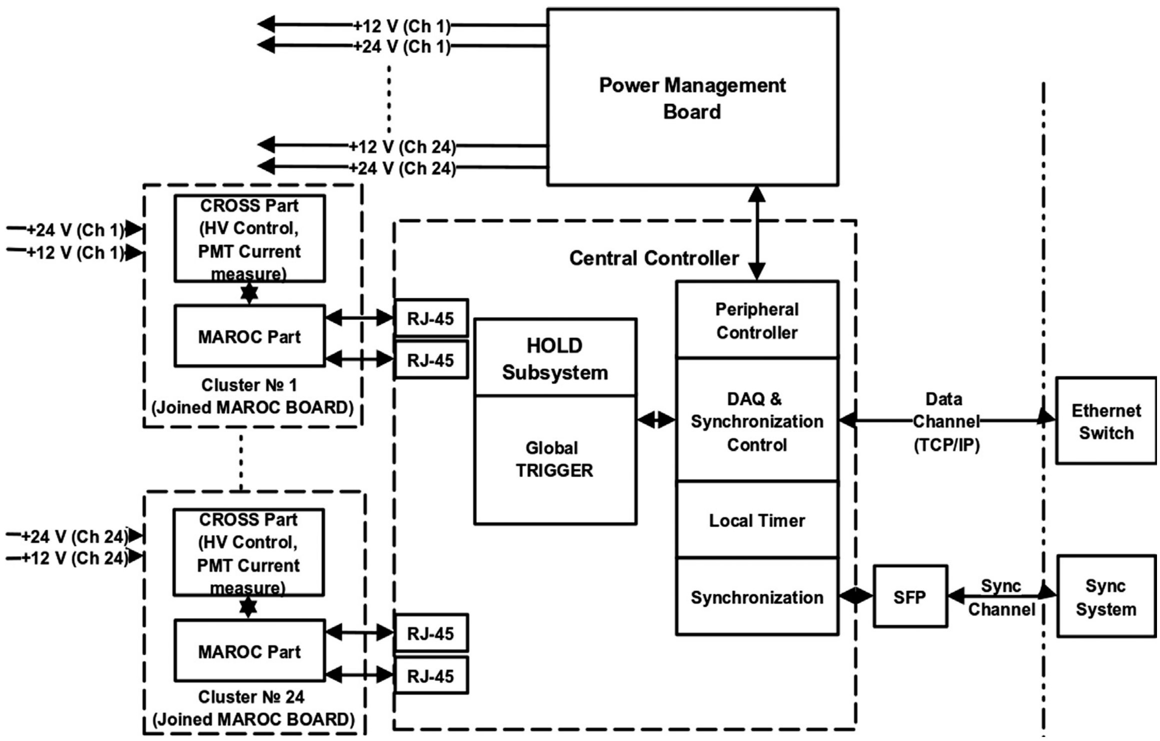

Fig. 2. The TAIGA-1 IACT camera electronics system.

the field of view of the pixel), the high voltage from the power source is removed.

A thermally insulated camera housing with a temperature control system is used for operation. The input window of the camera is made of plexiglass with a thickness of 14 mm to minimize the heat loss. The inner surface of the plexiglass is exposed to the heated air that circulates inside the camera housing. To protect the PMTs from daylight the input window is remotely closed using ordinary blinds. The camera electronics system (Fig. 2) can be divided into front-end, signal processing and readout electronics.

2.2.2. MAROC board

Each cluster includes a 64-channel board based on the ASIC MAROC-3 and the FPGA EP1C6Q240C6, the MAROC Board. Each PMT is connected to two of the 64 channels of the MAROC Board. A 30-fold difference in the pre-amplification coefficients of these channels allows for a linearity of the charge-code conversion up to 3000 ph.e. at a PMT gain of 10^5. After the preamplifier the signal is split and sent to a slow shaper (a charge-sensitive amplifier with variable integration time from 35 to 120 ns) and a comparator with a controlled threshold. The amplitudes of all the slow shapers are fixed by a common signal on the MAROC board called HOLD. These amplitudes are stored in a buffer and transferred via an analog multiplexed output to a 12-bit ADC. The output signal of the comparator is fed to the FPGA to form the local cluster trigger. A trigger will be generated if the number of signals from the outputs of the comparators exceeds a specified number for 15 ns. The local cluster trigger is sent to the Central Controller with the addresses of the hit pixels to form the HOLD signal, and also to the camera's Global trigger.

2.2.3. Central Controller

The Central Controller of the telescope is designed to control the MAROC boards, receive Local Trigger signals, generate HOLD signals, form Global Triggers and collect data from the MAROC boards. In addition, the Central Controller provides data transmission to the DAQ center and provides synchronization of the telescope with GPS time and with other parts of the TAIGA complex. The central controller is based on the Xilinx FPGA of the Zynq family, operating at a system frequency of 100 MHz. The local time clock of the central controller operates at a frequency of 200 MHz. Data exchange with the control computer takes place via the 1 Gbit Ethernet interface over a TCP/IP protocol. The data transfer rate is 500 Mbit/s, which ensures reading of events without losing data up to the camera trigger rate of 2 kHz. After receiving the first local trigger signal from a MAROC board, the Central Controller generates a HOLD signal for all MAROC boards. The time from the Central Controller receiving the TRIGGER signal to the formation of the HOLD signal at its outputs is no more than 10 ns.

The Global Trigger is based on the local cluster trigger and uses additional information: number of local triggers, position of pixels and etc. The Global Trigger is formed only if the hit pixels in a cluster are adjacent to each other ("topological condition"). By using topological conditions, the useless counting rate of Global Triggers due to random coincidences is decreased by 10 times. If a Global Trigger is not formed within 2 microseconds after the front of the HOLD signal, the HOLD signal is reset and the ADC operation is blocked. Fig. 3 shows the timing diagram of the camera trigger system operation. It includes the following steps:

- The local trigger is generated upon a coincidence of local PMT triggers and transmitted to the Central Controller.
- The HOLD signal is formed by the Central Controller on any local trigger and passed on to all MAROC Boards.
- If the global trigger is formed, then all ADCs on the MAROC Boards continue operation, if not, the operation of all ADCs stops.

2.3. TAIGA-Muon array

The use of particle detectors as one component of a combined detector complex provides new ways for gamma/hadron separation. As a first step, the Tunka-Grande installation using 380 scintillation counters with a size of $80 \times 80x4$ cm^3 formerly used at the EAS TOP and KASCADE-Grande arrays was set up [6]. In 2019, in addition to Tunka-Grande, work began on the construction of the TAIGA-Muon scintillation array with an estimated total detector area of about 2000 m^2.

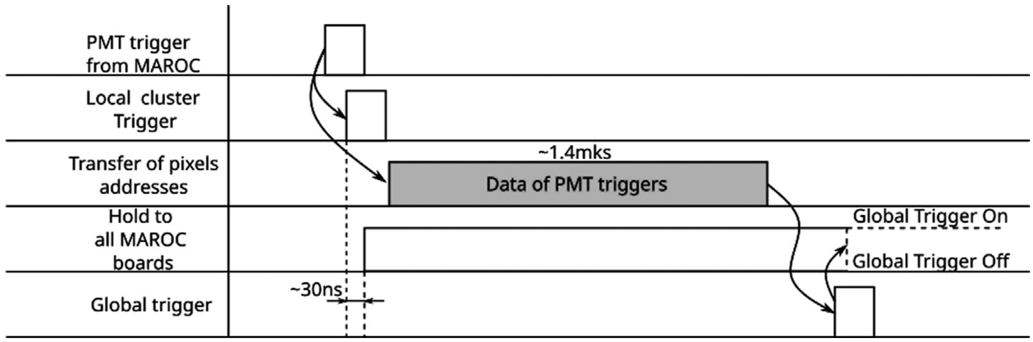

Fig. 3. Timing diagram of the camera trigger system operation.

The area of the TAIGA-Muon counter [7] is 1 m^2. The average signal amplitude during the passage of a muon for these counters is 20–25 ph.e. Based on the results of Monte-Carlo simulations using the CORSICA and GEANT4 software, the optimal geometric arrangement of the clusters of the TAIGA-Muon installation and scintillation counters inside each cluster was found.

3. Future plans

The next plans for the development of the TAIGA-1 installation include the deployment in 2022–2023 of 2 more IACTs and 200 m^2 of particle detectors (Fig. 1). The effective area for events detected by two or more telescopes in stereo mode will reach 0.9 km^2 for gamma-rays with an energy of more than 20 TeV. One of the problems in the joint operation of the TAIGA-HiSCORE installation and TAIGA-IACT is the significant difference in their apertures. The aperture of the IACT is 25 times smaller than that of the TAIGA-HiSCORE installation. In the future, it is planned to use Small Imaging Telescopes (SIT) with cameras with a FOV of 25–30° and an effective detection area of 1 m^2 to study the energy range above 80 TeV. With the operation of such telescopes, the percentage of joint events with the TAIGA-HiSCORE installation will increase by almost 10 times and for such joint events a high efficiency for separating events from gamma quanta will be achieved. The SITs are installed in a standard optical container of the TAIGA-HiSCORE array and connected to the DAQ and synchronization system of this array. The MicroFC-SMTPA-60035 SiPM used in the SITs has a fast output and a 6×6 mm^2 sensitive area. The camera matrix is assembled of 7-segment SiPM boards with 7 SiPMs on each of them. The fast output of each SiPM is connected to a two-stage preamplifier. The first stage works as a current-to-voltage amplifier–converter. The second stage is used to transmit the signal through a coaxial cable to the DAQ system. The FWHM of a single photoelectron pulse is about 20 ns and the amplitude at maximum SiPM gain ($5 \cdot 10^6$) is about 30 mV. A temperature sensor is installed on each SiPM board. Each SiPM power supply line has an ADC–DAC pair for constant monitoring and control of the gain of each SiPM. The further development of the TAIGA project is mainly due to the expansion of the TAIGA-HiSCORE installation. With an increase in the area of 10 times (with the creation of the TAIGA-10 setup), the number of events from the Crab Nebula for 100 h of observation will reach 300 at energies above 100 TeV, with a significance of $\sim 5\sigma$. Additional suppression of hadron background using wide angle SITs will increase this value to $\sim 10\sigma$

4. Conclusions

In 2021 the deployment and commissioning of the one-square-kilometre TAIGA-1 setup was finished. Its integral sensitivity is about $5 \cdot 10^{-13}$ TeV cm^{-2} sec^{-1} for the detection of gamma-quanta at an energy of 100 TeV over 300 h of source observation. There are four ways for the detection of gamma rays in the TAIGA experiment:

1. Autonomous operation of a single IACT for $E < 30$ TeV
2. Stereoscopic approach for large distances between the IACTs for $E > 10$ TeV
3. Hybrid approach: joint operation of the TAIGA-HiSCORE and the IACTs for $E > 40$ TeV.
4. Hybrid approach: joint operation of TAIGA-HiSCORE and muon detectors for $E > 300$ TeV

The TAIGA experiment is the northernmost gamma-ray experiment, and its location provides advantages for the observation of sources at large declination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work was performed at the UNU "Astrophysical Complex of MSU-ISU" (agreement 13.UNU.21.0007). The work is supported by the Russian Foundation for Basic Research (grants 19-52-44002, 19-32-60003), the Russian Science Foundation (grant 19-72-20067 (Section 2), and the Russian Federation Ministry of Science and High Education (projects FZZE-2020-0017, FZZE-2020-0024).

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