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TAIGA experiment: present status and perspectives

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Abstract: 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. TAIGA will be located in the Tunka valley, ~ 50 km West from Lake Baikal. The different detectors of the TAIGA will be grouped in 6 arrays to measure Cherenkov and radio emission as well as electron and muon components of atmospheric showers. The combination of the wide angle Cherenkov detectors of the TAIGA-HiSCORE array and the 4-m Imaging Atmospheric Cherenkov Telescopes of the TAIGA-IACT array with their FoV of 10×10 degrees and underground muon detectors offers a very cost effective way to construct a 5 km^2 array for gamma-ray astronomy.

Keywords: Gamma telescopes; Cherenkov detectors; Image processing

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1 Introduction

In recent years gamma-ray astronomy became the most dynamically developing field of astroparticle physics. More than 150 sources with gamma-ray energy spectra extending 1 TeV have been discovered and were studied. However not a single gamma-quantum with energy above 80 TeV has yet been detected, neither by former nor by current Imaging Atmospheric Cherenkov Telescopes (IACT) like HEGRA, H.E.S.S., MAGIC and VERITAS. The sensitivity of those facilities was optimized for the energy range 0.1 – 20 TeV. That was governed by physical goals of observations. Nowadays a lot of basic issues related to processes in the high and ultra-high energy range remain unanswered. These are the central for the new, so-called 4th generation of gamma detectors. It comprises instruments like CTA, HAWC and LHAASO and will have substantially higher sensitivity than existing telescopes, extending into the 100 TeV range. But even those sensitivities may not be sufficient to identify the highest energy sources.

TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) consists of wide-angle Cherenkov detectors, of IACTs, of electron and muon detectors and of shower radio emission detectors grouped in 6 six jointly operating arrays. It addresses crucial problems in both high-energy gamma-ray astronomy and cosmic ray physics.

The novel approach to combine HEGRA like IACTs of TAIGA-IACT array and wide-angle detectors of TAIGA-HiSCORE array within one instrument expands the capabilities of traditional IACTs towards higher energies. A wide-angle TAIGA-HiSCORE array allows to determine the main parameters of an EAS: shower axis direction, core position and energy. Preliminary analysis shows that combining this information with a shower image dramatically suppresses the cosmic ray background even for large distance (300–500 m) between core position and IACT. Since simultaneous shower detection by several IACTs is not required, the inter-telescope distance can be essentially increased up to 600–1000 m, which is impossible for the standard stereoscopic mode of IACT arrays. The common operation will allow us to use for primary particle identification a combination of data treatment techniques generally exploited in the data analysis of imaging and non-imaging (timing) instruments. It is a cost-effective experimental solution which allows to build an array of up to 5–10 km^2 area to study PeVatrons. To search for super high energy gamma rays, the radio array Tunka-Rex and the particle arrays Tunka-Grande and TAIGA-Muon will be used.

TAIGA is located in the Tunka valley, about 50 km from Lake Baikal in Siberia, Russia, at the site where since 2009 the Tunka-133 Cherenkov EAS detector has been in operation [1].

2 Tunka-133

The Tunka-133 array consists of 175 wide-angle Cherenkov detectors distributed over 3 km^2 area [1, 2]. The detectors are grouped into 25 clusters, each with 7 detectors — six hexagonally arranged detectors and one in the center. The distance between the detectors in the cluster is 85 m. Nineteen clusters are installed in an inner circle of 500 m radius — “inside” clusters, 6 clusters are placed at the distance of 700–1000 m from the center — “outside” clusters. An optical detector consists of the metallic cylinder with 50 cm diameter, containing the PMT (PMT EMI 9359 or Hamamatsu R1408) with hemispherical photocathode of 20 cm diameter. To provide the necessary dynamic range of 3×10^4, two analog signals, one from the anode and another one from the dynode, are read out. The cluster electronic [2] includes the cluster controller, 4 four channel FADC boards, adapter unit for connection with optical modules and temperature controller. The 12 bit and 200 MHz sampling FADC boards are based on AD9430 fast ADCs and FPGA XILINX Spartan XC3S300 microchip. The accuracy of the time synchronization between different clusters is of about 10 ns.

The energy spectrum and mass composition of cosmic rays in the range of 6–1000 PeV have been reconstructed using data from 5 winter seasons of measurements with the Tunka-133 array [3]. The spectrum has a rather complicated structure with different power-law index and points out reliably the existence of a “second knee” at 300 PeV, probably it is manifestation of a transition from galactic to extragalactic origin of the cosmic rays. We find a decrease of the mean (in logarithm) of the atomic number or composition, this lightening at energies higher than 100 PeV also points to the transition to extragalactic cosmic rays [3].

3 TAIGA-HiSCORE array

The principle of the TAIGA-HiSCORE array follows the idea outlined in [4]. It is rather similar to the one used for the Tunka-133 array. Again, this method is based on the sampling of the Cherenkov light of air showers, but with a threshold almost 20 times lower compared to the Tunka-133 array and with a much improved accuracy of EAS parameter reconstruction. The full TAIGA-HiSCORE will consist of an array of about 500 wide-angle (field of view 0.6 sr) light-sensitive detector stations, distributed with 75–150 m spacing over an area of several square kilometres. The array threshold for gamma-ray induced EAS is 40–50 TeV, for cosmic rays 80–100 TeV, at the Tunka site (680 m above

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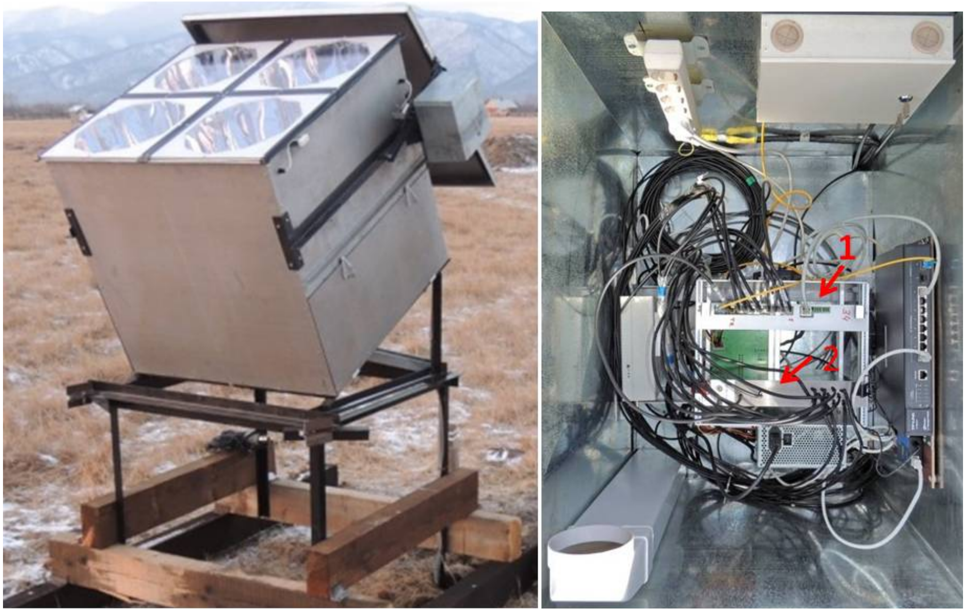

(a) **(b)**

Figure 1. The TAIGA-HiSCORE optical box (a) and inside electronic box (b).

sea level). The TAIGA-HiSCORE data allow to reconstruct the arrival direction of the EAS with up to 0.1 degree accuracy (for high energy events, see below) and the core position with 10 m accuracy.

Each TAIGA-HiSCORE [5] detector stations consists of two boxes. The first one is the Cherenkov box with four PMTs (figure 1a). Each PMT (R5912 or ET9352) is equipped with a light collector (Winston cone), with of 0.4 m diameter and a half opening angle of 30° made of ten strips of ALANOD 4300UP foil with reflectivity of ~ 90%. The cones increase the light collection area by a factor of four in comparison to bare PMTs. The anode signals of all 4 PMTs of the station are summed up, which leads to additional lowering of the energy threshold by a factor of 2.

A Plexiglass plate is used on top for protecting the PMT and the light collector from dust and humidity. It is possible to tilt the stations and thus to change the observed FoV. To reduce anode current the 6th dynode divider was used, the PMT gain is close to 10^4. The anode current in clean moonless night is in the range of 70–80 mkA. To expand the dynamic range the signal from the 5th dynode is also used. To compensate the low PMT gain, the anode and dynode amplifiers with gains 30 and 4, respectively, are used. This box also contains a controller for the slow control systems. The slow control system is used for opening and closing the station lid, for the HV supply control and monitoring, and for PMT anode current monitoring. The HV is switched off automatically, once the anode current exceeds a predetermined level.

The DAQ system (figure 2) consists of two parts: a central DAQ located in the main data collection and storage building (DAQ center), and a station DAQ in the electronics box (figure 1b) next to each optical detector. The main components of this temperature stabilized electronics box are the summator-board and the 8 channels DRS-4 board.

Each station is connected with the DAQ center by a fiber optic cable for the data transfer and synchronization. To synchronize all stations to sub-ns precision, a hybrid approach is used, see

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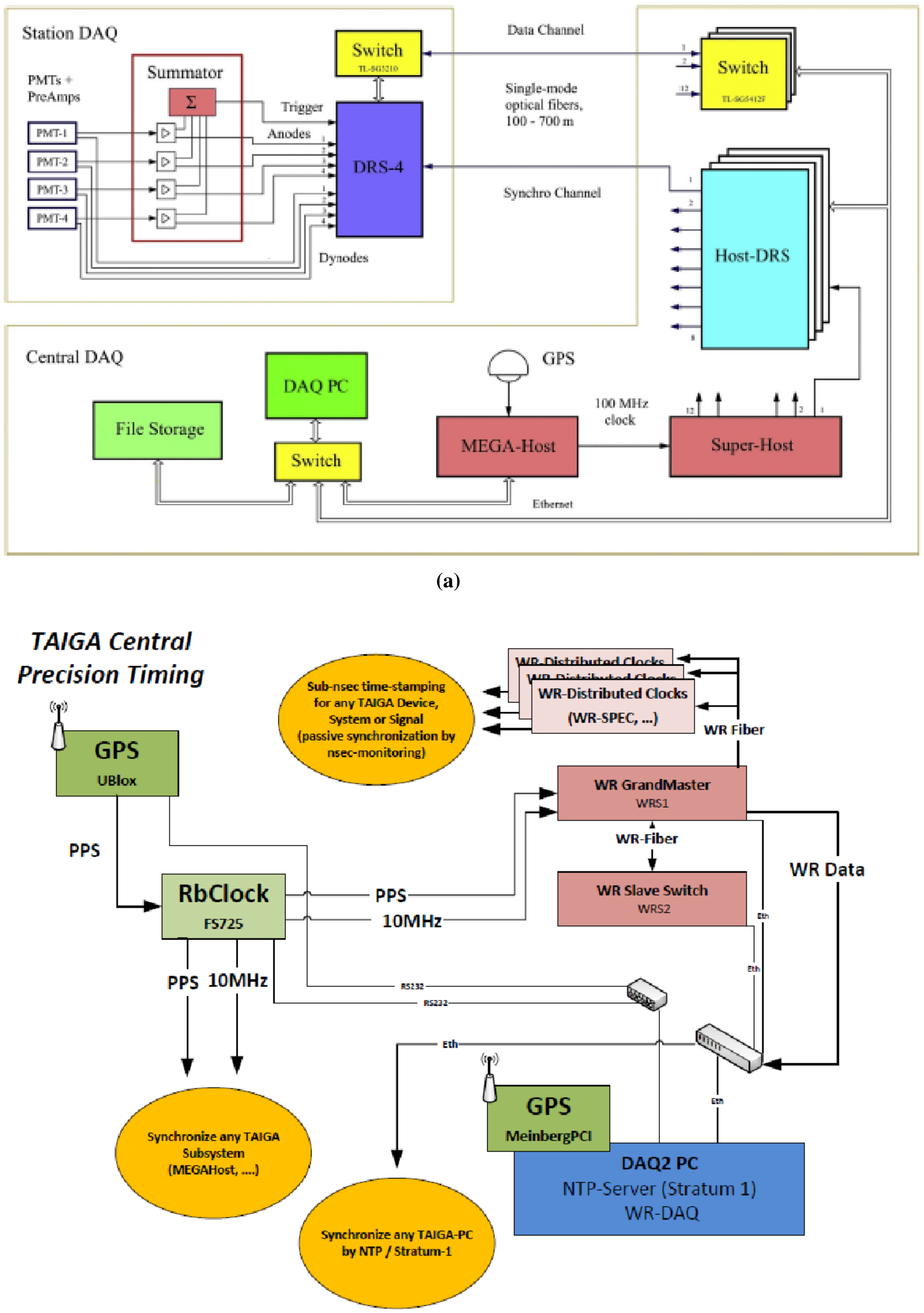

(a)

(b)

Figure 2. Structure of the data acquisition system of the TAIGA-HiSCORE array [5, 14].

figure 2. It combines a custom-made synchronization technique (100 MHz clocks distributed over fiber from the DAQ-center) [5], and a White Rabbit (WR) Ethernet-based timing system [5, 14]. The latter provides a central clock based on GPS-disciplined Rubidium Oscillator (GPSDO). The synchronization stability of the optical stations reaches up to 0.2 ns. Precision calibration of station time-offsets is achieved by external light sources. Each station operates independently from the others. The condition for formation of a local trigger signal is an excess of the sum of anode signals over a threshold level, set to approximately 200 p.e — which corresponds to a Cherenkov light flux of 0.3 photon cm^{-2} [6]. The single station trigger rate is about 10–15 Hz. Signals from anode and intermediate dynode are digitized with a step of 0.5 ns by an 8 channel DRS-4 boards for a 200 ns time window.

The reconstruction of shower parameters was performed using algorithms developed for the Tunka-133 array [1, 2] and for HiSCORE [15]. The accuracy of the arrival direction reconstruction strongly depends on the number of hit stations. The angular resolution is equal to 0.4–0.5° for events with 4–5 hit stations and about 0.1° for events with more than 10 hit stations. The accuracy of the reconstruction procedure was checked on MC simulation as well as with experimental data [7]. A method for absolute pointing calibration with the regularly detected ISS-LIDAR laser pulses (see [7]) is currently under development.

Front-end DAQ components with the 100 MHz synchronization (upper part), Central clock system based on WR with GSPDO/Rb (lower part).

4 TAIGA-IACT array

The imaging atmospheric Cherenkov telescope is of Davis-Cotton type with 34 mirrors, 60 cm diameter each, the focal length is 4.75 m. The camera of the telescope comprises 547 PMTs of XP1911 type with 2 cm photocathode diameter. The FOV of the camera is $10^\circ \times 10^\circ$ [8]. The camera consists of identical clusters, each with 28 PMTs (figure 3a). The basis of the cluster electronics is a 64-channel ASIC MAROC-3. The composition of the chamber includes a central DAQ controller and a power controller.

The clusters are mounted on the bearing duralumin plate. On the other hand, a Winston cone is installed on the plate to increase the collection of light from 3 times (figure 3b). The angle of each cone (35 degrees) covers all of the telescope's mirrors. The input window of the chamber is made of Plexiglass with a thickness of 15 mm. This thickness of Plexiglass is chosen to minimise the heat loss of the camera. This case of the camera is a quite complex device. The feature of this project, compared to others, is the operation in cold environmental conditions. A temperature control system, thermal insulation and some engineering solutions are used to guarantee the required internal conditions. The cluster consists of 4 groups of 7 photomultiplier tubes having a single charge dividers and a single high voltage power supply. Groups are combined in one cross-tab, where you set the DAC to control the high voltage sources and ADC to measure the current of all PMT of the cluster. The gain of a PMT is limited to the permissible value of the anodic background current from the light of the night sky. At the selected operation gain of 10^5 PMT current is 2 μa. At a current of 50 μa (the appearance of a bright star in the field of view PMT) high voltage divider the PMT is removed. On cross-card there is a 64-channel block of the digitized pulses on the basis of specialized integrated circuits, ASIC MAROC-3.

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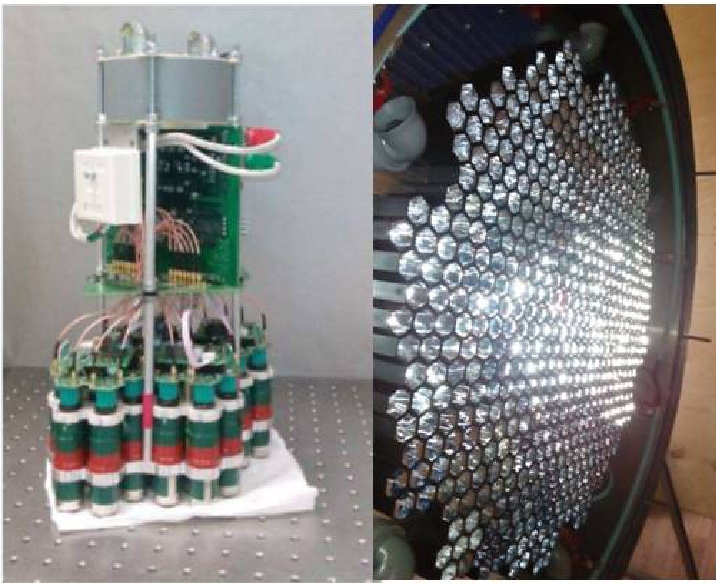

(a) (b)

Figure 3. a: cluster of PMTs; b: front view of camera- Winstone cones and Plexiglass windows.

4.1 ASIC MAROC3

The basis cluster board is the 64-channel ASIC MAROC3, which receives signals from the 28 PMTs (figure 4). Each channel includes a preamplifier with adjustable amplification (6 bit), a charge-sensitive amplifier and a comparator with an adjustable threshold. The ASIC chip comprises a 12-bit Wilkinson ADC. It has a multiplexed analogue output to an external ADC with a shaped signal proportional to the input charge, and 64 output trigger signals. The shaped signals are sent to the FPGA (FPGA EP1C6Q240C6), ensuring the formation of the local trigger (n-majority coincidences from 28 PMTs) of cluster. The FPGA controls the settings of the 64-channel amplifier-shaper-comparator and the ADC operation. The system of the MAROC3 control includes generating a local trigger, analog-to-digital converting, the loading of the MAROC3 configuration and the interface with the upper level system. Pulses from each PMT are divided by a passive splitter (see figure 5) and go to 2 channels with gains different by a factor 30. This results in a full dynamic range of 3000 photoelectrons. Before splitting, signals from each photomultiplier are sent to the current monitoring circuit.

In the exposition regime, the detection system of the camera provides amplification and discrimination of the PMT signals with a predetermined threshold, the selection of events corresponding to the light spot from an EAS (multiple PMT channels trigger within a specified time gate), and stores them in the internal buffer for processing in real time conditions. The minimum threshold is 5 ph.el.

4.2 Central DAQ controller

The structural scheme of the camera of the TAIGA-IACT [6] consists of PMT clusters and central DAQ controller. In December 2016 the first TAIGA-IACT (figure 7a) was put into operation. The

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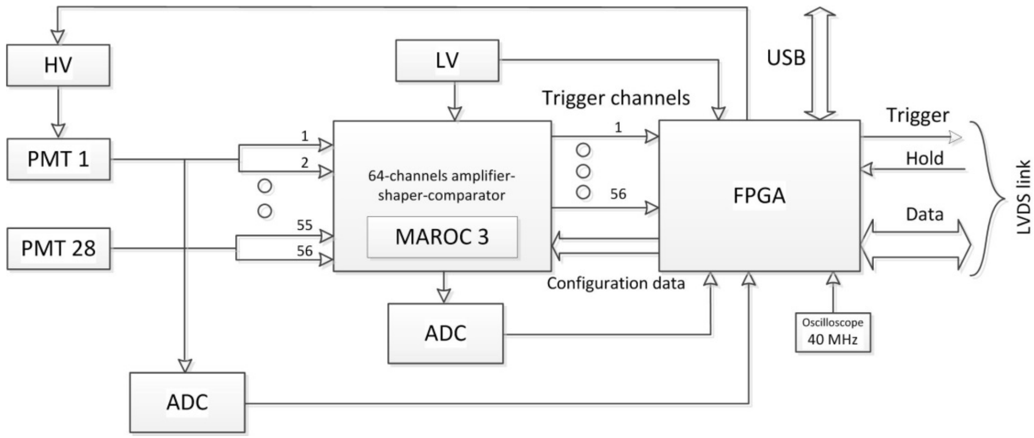


Figure 4. The block diagram of the MAROC board.

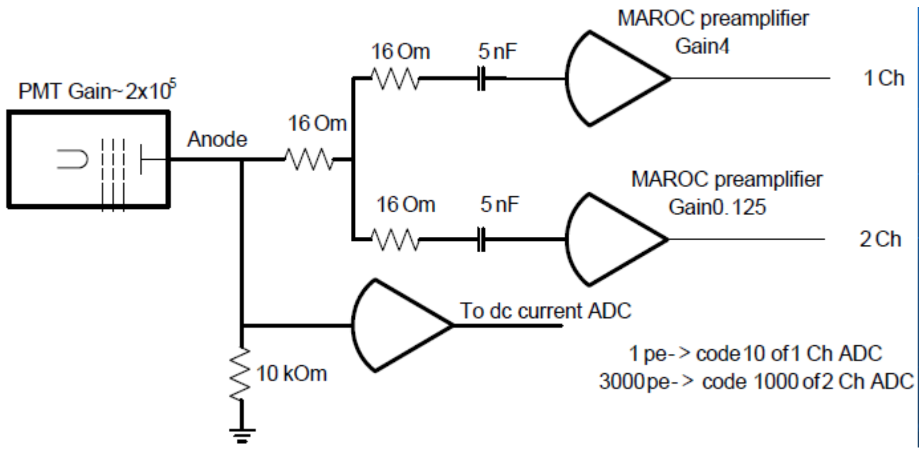


Figure 5. Splitter of PMT output pulses.

more systematic registration of EAS was begun at the end of January. Showers registered both by IACT and by TAIGA-HiSCORE have been already found. The example of such event is shown at figure 7b. The energy of these showers is 700 TeV. The core position of this EAS is at 200 m from IACT. The expected rate of such events is in good agreement with MC simulation.

5 A net of TAIGA particle detector

There are a lot of reasons to include the particle detectors into the hybrid detector complex of the gamma-observatory TAIGA. In particular, the number of muons in a charged cosmic-ray induced EAS is on average 30 times higher than in gamma-ray events [7], so the measuring of muon number is very effective way to suppress background. This should work well for the energy range above 100 TeV. The overall area of muon detectors should be 0.2–0.3% of the total area of TAIGA-HiSCORE, so we intend to construct a TAIGA-Muon array with an area 2000–3000 m^2.

As a first step for the future large array to detect EAS electrons and muons we constructed the Tunka-Grande array consisting of 19 scintillation stations, each of them with a surface and an underground parts. The stations are located at distances about 20 m from the centres of the

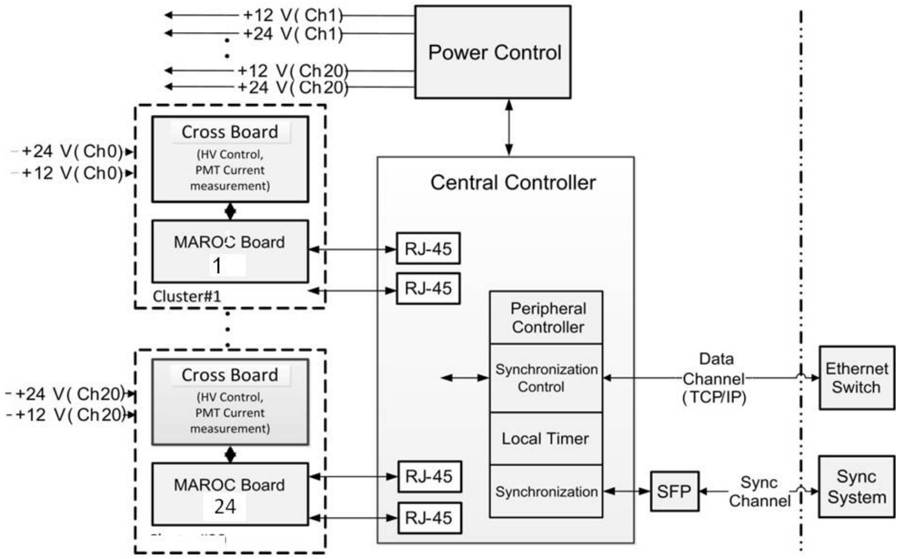
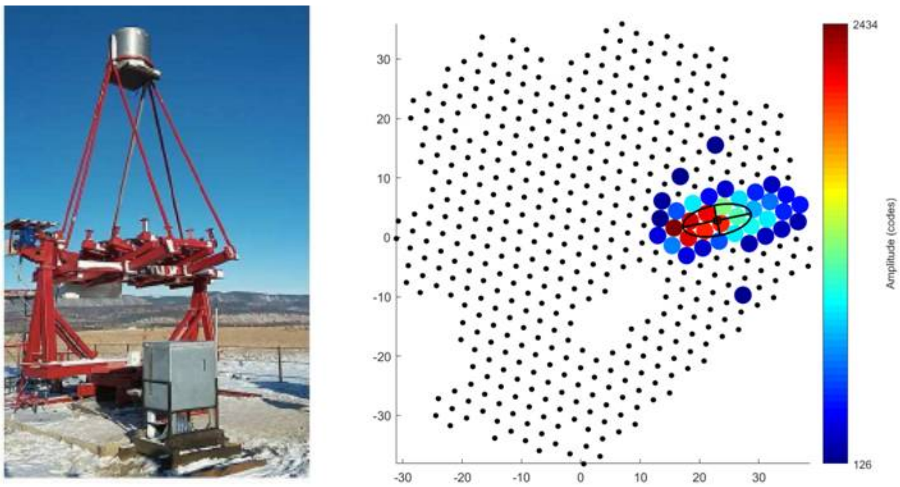


Figure 6. Structural scheme of TAIGA-IACT camera.



(a) **(b)**

Figure 7. a: view on TAIGA-IACT; b: example of event.

Tunka-133 clusters. In November 2015 the deployment of Tunka-Grande was completed and the array was put in operation. Each surface detector includes 12 scintillation counters with a size $80 \times 80\,\text{cm}^2$ formerly operated as part of the EAS-TOP and the KASCADE-Grande arrays. There are 8 of the same type counters in underground muon detectors. The simulation results [9] show that for energies $> 100\,\text{PeV}$ Tunka-Grande allows to reconstruct the EAS electron number with 10% precision, muon number — 25%, the EAS arrival direction with about 1.4 degree accuracy,

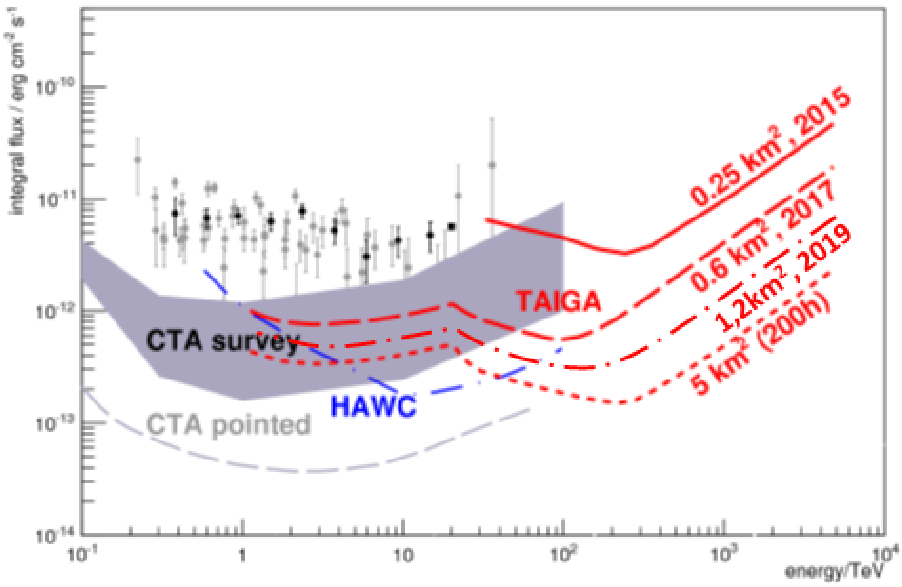


Figure 8. TAIGA (Tunka-HiSCORE and Tunka-IACT) point source sensitivity (very preliminary) in comparison with other experiments.

the core location — 20 m. New scintillation counters with size 100 × 100 cm for future particle TAIGA-Muon array are designed in BINP&NSU [10]. First cluster with 50 such counters should be deployed in autumn 2017.

6 The Tunka-Rex array

Tunka-Rex is the radio array of the TAIGA observatory [11]. At present time Tunka-Rex consists of 63 radio detectors. They cover area 3 km^2 and are located at distance 20 m about from Tunka-133 cluster centers and scintillation detectors of Tunka-Grande mainly with spacing 200 m. Upon a coincidence trigger of the Cherenkov or the scintillation detectors, both the radio and the air-Cherenkov or scintillation detector are read out in parallel. The electromagnetic field of the radio signal measured by Tunka-Rex is reconstructed in an effective bandwidth of 35–76 MHz. Details on the detector setup and its calibration can be read in reference [12]. The Tunka-Rex energy precision seems to be at least as good as the published Tunka-133 resolution of 15%. The X_{max} precision of Tunka-Rex is roughly 40g/cm^2 [13] and can be slightly increased.

7 Conclusion

In the end of 2017 TAIGA setup should include 60 detector stations of the TAIGA-HiSCORE array and 1 Imaging Atmospheric Cherenkov Telescope of the TAIGA-IACT array. The effective area of the setup should be about 0.6 km^2. Figure 8 shows the point source sensitivity.

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Combined operation of the first Cherenkov telescopes of TAIGA-IACT and the TAIGA-HiSCORE array in the energy range of 50–100 TeV will yield the sensitivity of the order of 10^{-13} erg/cm^{-2}s^{-1} (requiring detection of a point source with 5σ confidence level in $\sim$ 500 hours of observation). Such a sensitivity would give us a good chance to measure the energy spectrum of gamma rays from the Crab nebula and Tycho~SNR, the main PeVatron candidates. For TAIGA placed at 51° N/L this source may be observed during more than $\sim$ 200 hours per year, taking into account 50% of good weather condition. This sensitivity level would allow us to search for the signals from the sources observed by IceCube in neutrinos, if these sources have Galactic origin, and would allow make a survey for new PeVatrons. Figure 8 showers the TAIGA point source sensitivity in comparison with other experiment.

Signals from the nearby extragalactic sources Mrk421 and Mrk-501 will be also studied in order to investigate the gamma-ray absorption on intergalactic background radiation and to search for axion-photon transitions. The study of gamma radiation in the high energy range is of interest not only for astrophysics, but also for testing theories predicting a violation of Lorentz invariance and for searching for super-heavy dark matter.

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