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The TAIGA experiment: From cosmic-ray to gamma-ray astronomy in the Tunka valley

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ABSTRACT

We present physical motivations and advantages of the new gamma-observatory TAIGA (Tunka Advanced Instrument for cosmic ray physics and gamma-ray astronomy). TAIGA will be located in the Tunka valley, 50 km to the west of Lake Baikal, at the same place as the integrating air Cherenkov detector for cosmic rays Tunka-133. The TAIGA array is a complex, hybrid detector for ground-based gamma-ray astronomy for energies from a few TeV to several PeV as well as for cosmic ray studies from 100 TeV to several EeV. The array will consist of a wide angle Cherenkov array – TAIGA-HiSCORE with 5 km^2 area, a net of 16 IACT telescopes (with FOV of about $9.72^\circ \times 9.72^\circ$) as well as muon and other detectors. We present the current status of the array construction.

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1. Introduction

In recent years gamma-ray astronomy has become the most dynamically developing field of astroparticle physics. More than 150 TeV gamma-ray sources have been discovered and 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 [1], H.E.S.S. [2], MAGIC [3] and VERITAS [4]. The sensitivity of those facilities was optimized for the energy range 0.1–20 TeV. Nowadays many basic issues related to processes in the high and ultra-high energy range remain unanswered. These are central for the new, so-called 4th generation of gamma detectors. It comprises instruments like CTA [5], HAWC [6] and LHAASO [7] 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 in our Galaxy.

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. It addresses crucial problems in both high-energy gamma-ray astronomy and cosmic ray physics. Its main feature is the common operation of IACTs and wide-angle detectors. That allows increasing the IACT spacing up to 600–1000 m, which is impossible for the standard stereoscopic mode of IACT arrays. This approach has the potential to reduce the number of expensive telescopes required for successful observations by a factor of four or more. The coincident 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. TAIGA will be located in the Tunka valley, about 50 km from Lake Baikal in Siberia, Russia, where the Tunka-133 Cherenkov EAS detector is in operation since 2009 [8].

2. The Tunka-133

The Tunka-133 detector is a non-imaging, shower front sampling array consisting of 175 wide-angle Cherenkov detectors distributed over an area of 3 km^2 [8]. Each detector consists of a PMT (Emi 9359 or Hamamatsu R1408) with a hemispherical photocathode of 20 cm diameter, an entrance window heating system and a case with a UV-transparent entrance window and remote-controlled lid. The measurements require an electronics dynamic range of $3 \cdot 10^4$. For the purpose, two analog signals, one from the anode and another one from the dynode, are processed. The FADC based read-out electronics has 12 bit capacity and a 200 MHz sampling rate and is based on AD9430 fast ADCs and FPGA XILINX Spartan XC3S300 microchips.

3. The TAIGA-HiSCORE

The TAIGA-HiSCORE operation principle follows the idea outlined in [9]. Like for Tunka-133, the method is based on the sampling of the Cherenkov light front from air showers, but with lower energy threshold and higher time-amplitude resolution. TAIGA-HiSCORE will consist of an array of 500 wide-angle (FoV $\approx$ 0.6 sr) optical detectors, distributed with a spacing of 75–200 m over an area of 5 square kilometers during the first stage. Probably the array will be extended in the future. The energy threshold for gamma-ray induced showers is about 50 TeV, for cosmic rays 100 TeV. TAIGA-HiSCORE data allows reconstructing the arrival direction of the air shower with an accuracy of about 0.1°, the axis position with 5–6 m, the energy with 10–15% and the shower maximum height Xmax with 20–25 g/cm^2 accuracy. A detailed description of TAIGA-HiSCORE is presented in [10].

4. The TAIGA-IACT

The TAIGA-IACT detector will consist of 16 IACTs distributed over an area of 5 km^2 with a spacing of up to 600–1000 m. The general view of the telescope is shown in Fig. 1. The compound telescope reflector has a Davis-Cotton design with a focal length of 475 cm and consists of 34 spherical mirrors with 60 cm diameter. The mount of the telescope is of alt-azimuth type with the following parameters:

- Zenith angle motion range from −10° to 95°
- Azimuth angle motion range from 0° to 410°
- Motion angular accuracy 0.01°
- Slewing speed 4–8°/min

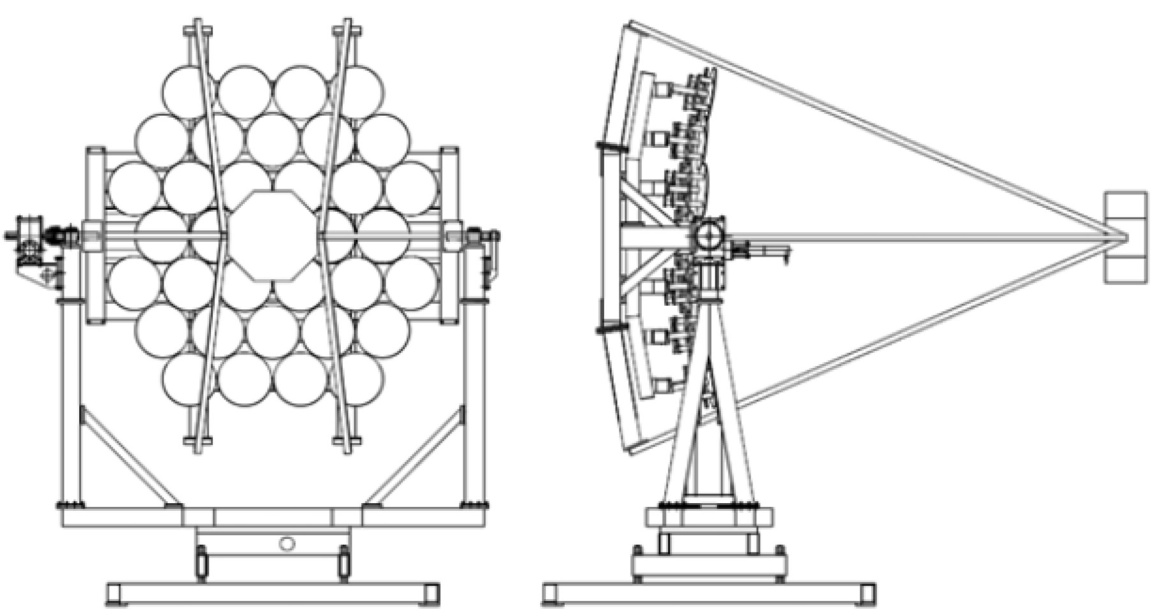

Fig. 1. General plan view of the TAIGA IACT.

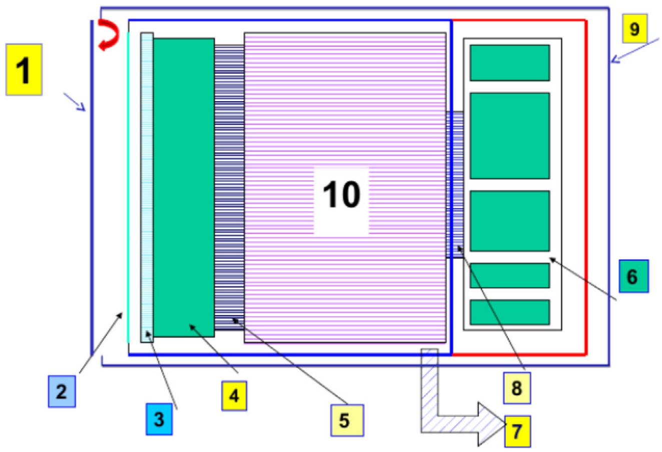

Fig. 2. Schematic view of the camera conceptual design. See explanations in the text.

The visual instrument of the telescope is a PMT-based camera. Fig. 2 illustrates its conceptual design. To shield the camera against solar radiation, the remote control lid (1) is placed at a small distance before the entrance window (2), made of plexiglass without UV-absorber. The small space between the lid and the window is required for air flow. Behind the window there is a matrix of PMTs (4) equipped with compound parabolic concentrators (3) (CPC, also called Winston cone), the PBC HV system (5) and the signal processing read-out electronics based on ASIC MAROC 3 and DRS4 chips (10). The camera is equipped with a set of controllers and power supplies (6) and a system of connectors (8). All components are placed in a rigid environment-controlled case (9). The case has a connection to the environment control system (7).

The case of the camera is quite a complex device. The feature of this project, compared to others, is the operation under cold environmental conditions. A temperature control system, thermal insulation and some innovative engineering solutions are used to guarantee the required internal conditions.

The camera matrix consists of 547 photomultipliers. It will have a field of view (FOV) of $9.72^\circ \times 9.72^\circ$ and an angular size of 0.36° per pixel. For the first 3 IACTs we intend to use PMT XP1911 with a window of 15 mm diameter. Each PMT is equipped with a hexagonal Winston cone with an entrance size of 30 mm and an exit aperture of 15 mm diameter. The whole array of pixels is divided into clusters of 28 PMTs each. The cluster electronics comprises several boards: four divider boards of the 7 PMT groups, four PMT power supply boards, four boards with DAC for the high voltage control and ADC for measurement of the PMT current and signal processing. The power supply board provides control of the PMT voltage up to -1600 V and control of the current up to 1 mA. The accuracy of the output voltage setting is about 0.2%. The maximum power consumption is 4.5 W. Signal processing is carried out by a PMT DAQ board based on MAROC3.

The novel approach to combine IACTs and wide-angle detectors within one instrument expands the capabilities of traditional IACTs towards higher energies. A wide-angle instrument allow ones to determine the shower axis direction (with an accuracy of 0.1°), the core position and the X_{max}. Preliminary analyses show that combining this information with a shower image dramatically suppresses the cosmic ray background. Since simultaneous shower detection by several IACTs is not required, the inter-telescope distance can be essentially increased. This allows us to cover the area required for collecting large statistics at high energies with much fewer telescopes.

5. TAIGA-Muon and Tunka-Grande

The use of particle detectors as one component of a combined detector complex provides new ways to understand the nature of the shower. In particular, the number of muons in a charged cosmic-ray induced EAS is on average 30 times higher than in gamma-ray events [11]. Therefore measuring the muon number helps effectively suppressing the cosmic-ray background. Moreover the muon number depends on the primary nuclear charge, providing important information on the primary composition 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 of 2000–3000 m^2.

As a first step to a future large particle detector array ("Tunka-Grande"), 19 scintillation stations were constructed and put into operation, with each of the stations having a surface and an underground part. A surface station includes 12 scintillation counters with a size of $80 \times 80 \times 4$ cm^3 formerly operated as part of the EAS-TOP and the KASCADE-Grande arrays. There are 8 counters of the same type located underground and operated as muon detectors. The Tunka-Grande DAQ, the synchronization and control systems are practically the same as that of the Tunka-133 array. Simulation results show [12] that for energies above 10 PeV, Tunka-Grande allows reconstructing the EAS electron number with a precision of 10%, the muon number with 25%, the arrival direction of the EAS with an accuracy of about 1.4°, the axis position with 17 m and the energy with 18% accuracy.

For the future TAIGA-Muon array we have designed a rather cheap and effective detector shown in Fig. 3. At present roughly one sector (one quarter) of the detector is used for tests. The prototype consists of a polystyrene-based scintillator in the form of an isosceles right triangle. The length of its hypotenuse is 98 cm, the thickness of the plate is 2 cm. Along the legs of the triangle two wavelength shifting bars are arranged. The bars are made from PMMA plastic doped with BBQ dye. The cross-section of the bar is 3×17 mm^2. The light from the bars is detected by a FEU-84 photomultiplier (QE = 12% at 500 nm). The reflectors made from PTFE film are placed on the far ends of the bars. The prototype was tested with cosmic ray muons in several points. The mean number of detected photoelectrons from a single muon varies from 9 to 15. Based on these results we estimate the number of photoelectrons in the future counter to be larger than 20. This will be achieved by using a photomultiplier with higher quantum efficiency than the FEU-84 and by optimizing the amount of BBQ dye in the WLS bar with a larger cross-section of 5×20 mm^2. We assume that 20

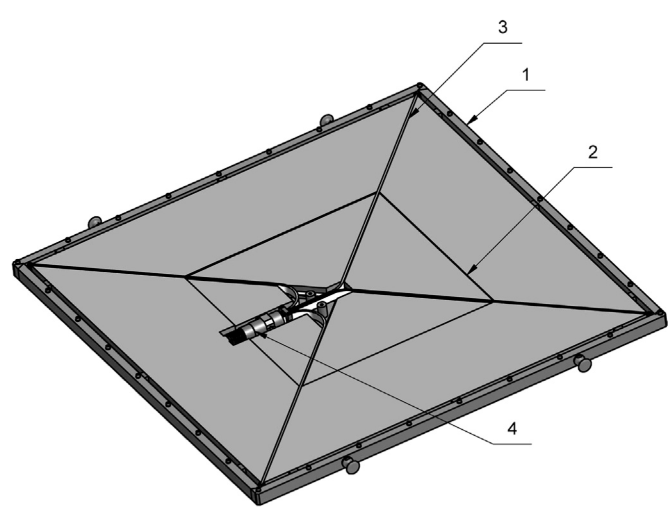

Fig. 3. The design of the muon detector: 1 – counter frame, 2 – scintillator, 3 – wavelength shifting bars, 4 – PMT. The size of the active surface is 1×1 m^2.

detected photoelectrons will be enough to ensure 100% detection efficiency for cosmic muons and a long lifetime of the detector.

The possibility to reconstruct the direction, energy and the EAS maximum by Tunka-133, TAIGA-HiSCORE and Tunka-Rex and to estimate the number of muons using Tunka-Grande and TAIGA-Muon data will allow us to start searching for local and diffuse gamma radiation with energies higher than 1 PeV.

6. The Tunka-Rex array

Detection of shower radio emission is another technique that can be used to measure shower parameters. The radio signal is sensitive to the shower energy and X_{max}. It is mainly due to the geomagnetic deflection of relativistic electrons and positrons in the shower inducing a time-variable current.

Tunka-Rex is the radio array of the TAIGA observatory. At present it consists of 44 radio detectors. They cover an area of 3 km^2 mainly with a spacing of 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 electric field of the radio signal recorded by Tunka-Rex is reconstructed in an effective bandwidth of 35–76 MHz. Details on the detector setup and its calibration can be found in reference [13].

There is a clear correlation between the energy and Xmax reconstructed from the radio amplitude measured by Tunka-Rex and the energy reconstructed from the air-Cherenkov light measured by Tunka-133. The Tunka-Rex energy precision seems to be at least as good as the published Tunka-133 resolution of 15%. The total scale uncertainty of Tunka-Rex is dominated by the uncertainty of the amplitude calibration, and in total is of the order of 20%. This is comparable to the scale uncertainty of particle detector arrays, like KASCADE-Grande [14]. The X_{max} precision of Tunka-Rex is roughly 40 g/cm^2, and can be slightly increased [15]. This resolution is sufficient to statistically distinguish light from heavy primary particles. Independent muon measurements on the ground with the new Tunka-Grande array can enhance the total accuracy since the electron-muon ratio provides mass information complementary to Xmax [16].

As a next step, the radio measurements can be combined with the particle detectors to increase the total accuracy for the air-shower parameters. While the antenna arrays provide a calorimetric measurement of the electromagnetic component and sensitivity to the longitudinal shower development, measurements of the secondary electrons and muons at ground give a complementary access to the energy and mass composition of the primary particles. In the future, this concept can easily be applied to the larger muon array of TAIGA by installing additional antennas.

7. Conclusions

In 2015, the TAIGA collaboration continued the construction of a detector complex in order to search for new Galactic sources of gamma-rays with energies higher than 20–30 TeV. Signals from the nearby extragalactic sources Mrk421 and Mrk-501 will also be studied in order to investigate the gamma-ray absorption by the 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. The combined operation of the first Cherenkov telescopes of TAIGA-IACT and the TAIGA-HiSCORE array in the energy range of 30–200 TeV will yield a sensitivity of the order of 10^{-13} erg cm^{-2} s^{-1} (requiring detection of a local source with 5σ confidence level in 500 h of observations). Such a sensitivity would give us a good chance to measure the energy spectrum of gamma rays from the Tycho SNR, one of the main PeVatron candidates. For TAIGA placed at 53°N/L this source may be observed during more than 200 h in one year, taking into account 50% of good weather conditions. This sensitivity level would allow us to search for signals from the sources observed by IceCube in neutrinos if these sources have a Galactic origin and would also allow us to make a survey for new PeVatrons.

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