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

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ABSTRACT

The combination of a wide angle timing Cherenkov array and Imaging Atmospheric Cherenkov Telescopes operated in mono mode offers a cost-effective way to construct a few square kilometers array for ultrahigh-energy gamma astronomy. The first stage of the TAIGA Observatory (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is described here. It will comprise TAIGA-HiSCORE - 120 wide angle Cherenkov stations distributed over an area of 1.0 km^2 and three IACTs (TAIGA-IACT).

1. Introduction

Detection of gamma rays is one of the most efficient ways of investigating galactic and metagalactic sources of high-energy cosmic rays and of solving many other problems of astroparticle physics. By the present time, the most significant results in ground-based gamma-ray astronomy have been obtained using the arrays HEGRA, H.E.S.S., VERITAS, and MAGIC, which include from 2 to 5 Imaging Atmospheric Cherenkov Telescopes (IACT).

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Fig. 1. Overview of the TAIGA observatory: the array of TAIGA-HiSCORE stations and the IACTs, and the DAQ-center. By early 2020, 1 km^2 of HiSCORE and three IACTs will be installed.

A conceptually new approach to the studies of high-energy gamma rays is being developed within TAIGA gamma-ray observatory (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) with a hybrid system of jointly functioning wide-angle timing and imaging Cherenkov detectors [1]. A 1 km^2 TAIGA prototype setup is currently being constructed in the Tunka Valley 50 km from Lake Baikal. Fig. 1 gives an areal overview of the TAIGA setup, with its main components: the wide-angle Cherenkov stations of the timing array TAIGA-HiSCORE, the first IACT of the TAIGA-IACT array and the DAQ-center. The main feature of the TAIGA approach is that the reconstruction of energy, position, and direction of the EAS is performed with the data of the timing array TAIGA-HiSCORE. To discriminate gamma rays from the hadron background, the IACTs are used. Very important for this purpose is that each IACT can operate in mono-mode and that the distance between them can be increased at least up to 600 m, and possibly up to 1000 m.

2. The wide-angle timing array TAIGA-HiSCORE

Each station of the TAIGA-HiSCORE array comprises four photomultipliers (PMT) with a photocathode of 20 to 25 cm diameter (ET9352KB, R5912, or R7081) and the station data acquisition system (DAQ). Each PMT is equipped with a Winston cone made of a highly reflective material Alanod 4300 UD, which increases the effective light-collecting area by a factor of four. The FoV (Field of View) of the Winston cone is about 0.6 sr. The DAQ of TAIGA-HiSCORE has a hierarchical structure (Fig. 2). The Cherenkov stations of the array are grouped in clusters of approximately 30 detectors each. The main components of the Cherenkov station DAQ are analog summators and an 8-channel ADC based on the DRS-4 board, by means of which the signals from the anodes and the fifth dynode (to expand the dynamic range) of each PMT are digitized with a 0.5 ns step within a 200 ns window after the formation of the trigger. For moonless nights the trigger rate of a TAIGA-HiSCORE station is 10–15 Hz. The energy threshold of the array is 80–100 TeV for hadronic air showers and 40–50 TeV for showers initiated by gamma rays. Each HiSCORE station is connected to its Cluster Center by an optical cable, which serves for data transmission and synchronization. To reach best pointing precision of TAIGA-HiSCORE (~0.1 deg), a relative time synchronization between HiSCORE stations of sub-nsec precision is required [2]. In addition, also IACT events should be time-stamped with a few nsec precision, to be included into the array pointing reconstruction. As indicated in Fig. 2, two time-synchronization systems are operated in parallel, both receiving the same front-end trigger signals: A custom system using a 100 MHz clock distributed over optical fibers, and a White-Rabbit based system [1,3,4]. The latter is referencing to a precision GPS TimeServer (Meinberg Lantime M1000).

An important requirement for the TAIGA synchronization systems is their long-term stability. A precision cross comparison of stability of both systems is given in Fig. 3. The analysis uses the trigger times as

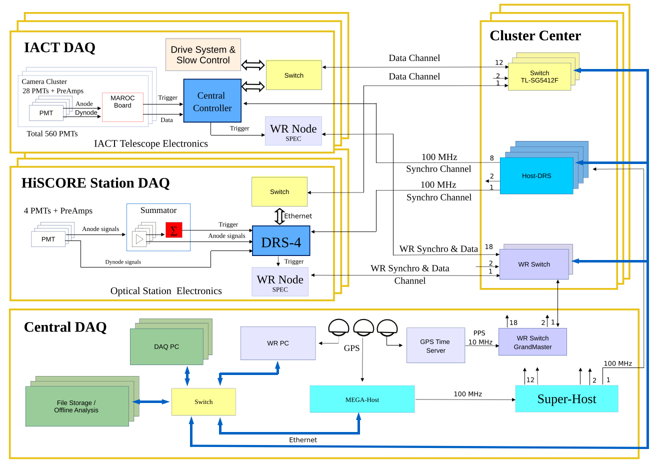

Fig. 2. The TAIGA-DAQ, comprising the DAQ-center, the Cluster centers, and the DAQ in HiSCORE-stations and IACTs. Indicated are Front-End components and both independent timing systems, as well as central servers and clocks.

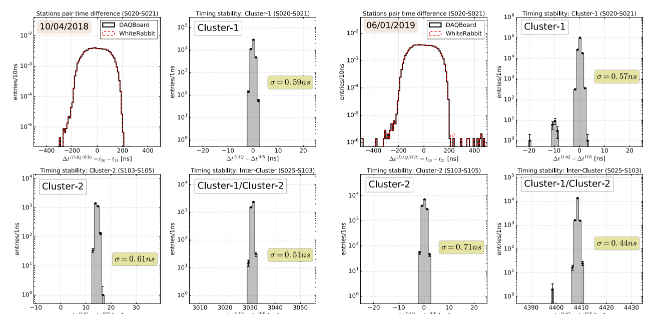

Fig. 3. Precision test of the two independent TAIGA timing systems, comparing the trigger timestamps on an event-by-event basis. Two days shown: **Left**: 10/04/2018, **Right**: 06/01/2019. (a) **Upper left**: time difference for two channels, as directly measured by the WR- and the 100 MHz systems ("DAQ"). (b) **Upper right**: difference of the times from (a) for each event, $\Delta t^{DAQ} - \Delta t^{WR}$. (c) **Lower left**: same as (b) for two channels from HiSCORE Cluster-2. (d) **Lower right**: same as (b) for two channels from HiSCORE Cluster-1 and Cluster-2.

obtained from both systems on an event-by-event basis. by comparing the difference of time differences $\Delta t^{DAQ} - \Delta t^{WR}$ of trigger times, see Fig. 3 for details. The conclusion of this test is an excellent combined and individual stability performance of the two TAIGA timing systems: the rms of the differences of time-differences is < 0.7 ns, which implies a rms well below < 0.5 ns for each time-system independently. We are currently investigating the long-term stability of the absolute offsets.

Fig. 4 shows a long-term environmental test of the stability of the time synchronization between DAQ-center and HiSCORE cluster number 2 for the WR-system: A loop-back fiber is routed from the WR-switch WRS-4 (layer-2) in HiSCORE cluster 2 back to the master-clock (WRS-1) in the center. WRS-4 is found to be stable on the nsec-level (stable phase in upper panel), despite 40 degrees of ambient temperature variation (lower panel). This result supports the conclusions drawn from the test shown in Fig. 3 above, and is part of a larger systematic test setup operating in TAIGA [5,6].

3. The TAIGA-IACT

The Imaging Atmospheric Cherenkov Telescopes of the TAIGA-IACT array have a composite reflector of Davis–Cotton design consisting of 34 glass mirrors with 60 cm diameter each. The reflector has a total diameter of 4.3 m. Its focal length is 4.75 m. For protection from frosting, heated air is blown over all mirrors. The telescope camera includes a matrix of 560 PMTs $XP1911$ equipped with a Winston cone

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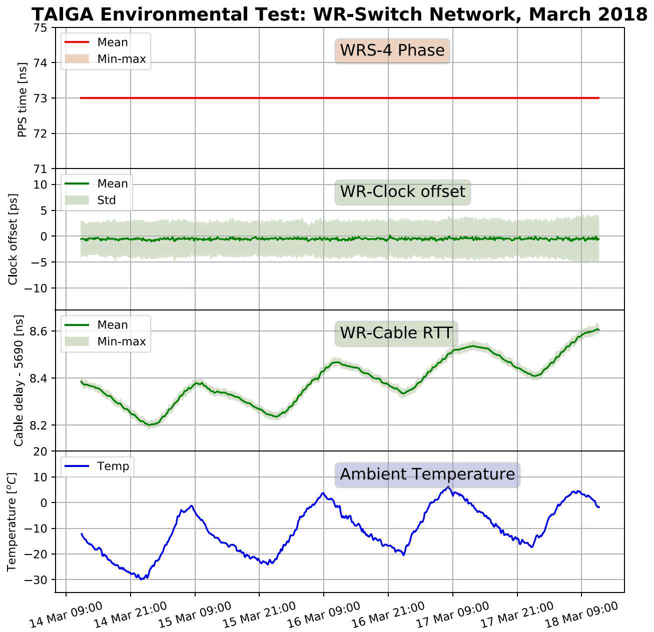

Fig. 4. Long-term environmental test of White Rabbit time-synchronization at the TAIGA Observatory [6]: a WR-network loop-back test. WR-Switch-4 (cluster 2, layer 2) synchronizes SPEC-T2, which is time-stamping the WRS-1 PPS. The phase is absolutely stable (upper panel) despite 40 degree temperature changes (lower panel), which modulates the (WR estimated) cable round-trip-time RTT.

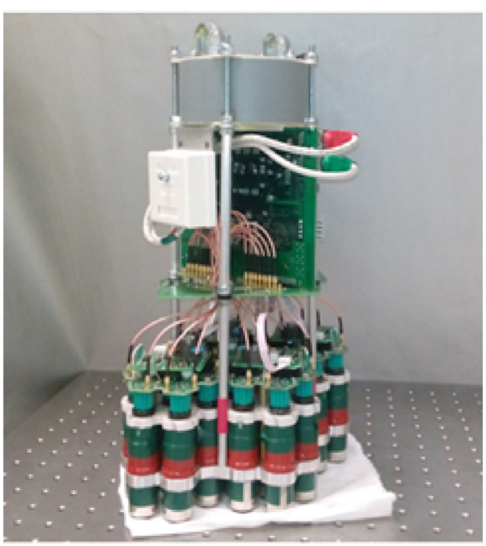

Fig. 5. TAIGA-IACT: a camera cluster of 28 PMTs.

with an entrance size 300 mm. The PMTs have been formerly exploited in the ZEUS experiment in DESY. The sensitive area of the camera has a diameter of about 81 cm, the FoV is 9.6 degrees. The camera design guarantees its reliable operation in cold winter. The camera PMTs are grouped into clusters (Fig. 5). Each cluster contains four groups of seven PMTs, four divider boards, four PMT power supply plates, four daughter plates with the DAC for the high-voltage source control, and the ADC for the measurement of the PMT current. Signal processing is carried out by a PMT DAQ board [7] based on the 64-channel ASIC MAROC3.

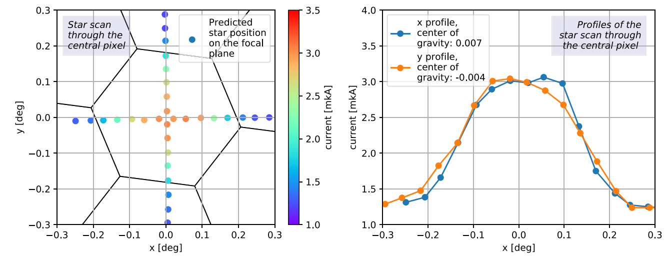

Fig. 6. Telescope pointing test based on the measurement of anode current during special tracking runs. Left: calculated positions of a bright star on the focal plane are shown by dots. Current values on the central PMT are given by the color scale. Black lines indicate the camera pixels. Right: current profile as measured on the central PMT for a specific x- and y-scan.

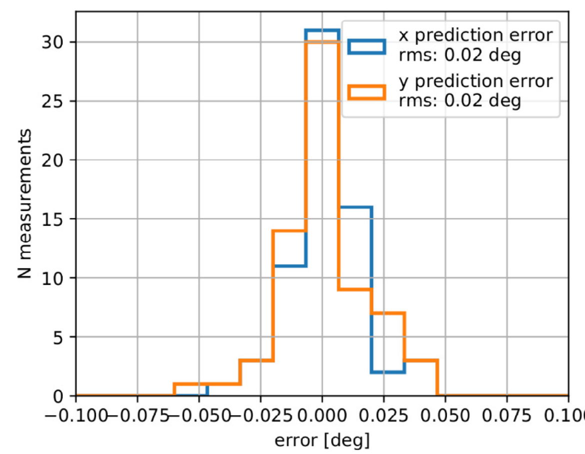

Fig. 7. Distribution of differences between center of gravity, calculated from measured current profiles and pixel positions for central and non-central pixels. The distribution includes measurements at telescope inclinations between 40 and 80 deg, for November 2018 to March 2019.

3.1. TAIGA-IACT: Telescope pointing

The telescope tracking system consists of two Phytron hybrid stepper motors and two 17-bit shaft encoder and limit switches connected to the PhyMOTION control unit. A CCD-camera Prosilica GC1380 is installed on the telescope dish at a distance of 1 m from the telescope optical axis. The CCD-camera is used to determine the telescope pointing direction by its images and to perform calibration measurements. The trajectory for the telescope movement is calculated using the SOFA software and applying a pointing model. The telescope tracking system is controlled by software developed within the EPICS framework [8]. As a test of the telescope pointing, special tracking runs are performed. These runs include the cross-like scan (see Fig. 6, left) of a bright star near the central PMT of the camera. During the scan, the anode current of the central PMT as well as the drive system information are recorded. For each measurement, the bright star position on the focal plane is calculated to obtain the current profiles along the X and Y axis in the PMT coordinate system. From the obtained current profiles along the X and Y axis, the center of gravity is calculated, see Fig. 6, right. The difference between the PMT position and the center of gravity is the telescope mis-pointing value. This calibration procedure is performed several times at the beginning and the end of each 2–3 weeks observation period.

During the central pixel-scans described above, also other stars and their corresponding current profiles are obtained. Using the method described for the central pixel, the differences between expected and measured center of gravity are obtained. The distribution of points measured between November 2018 and March 2019 is shown in Fig. 7.

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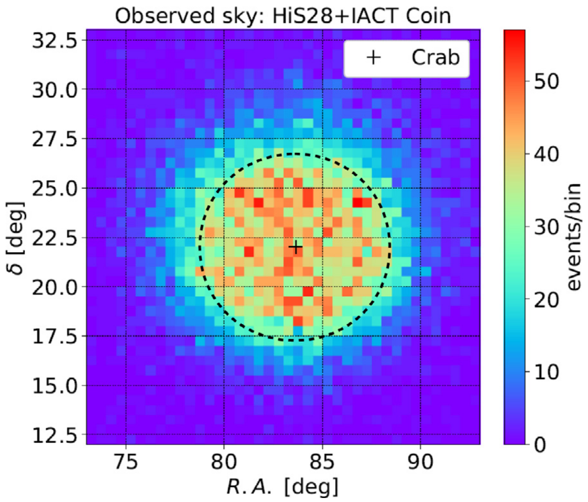

Fig. 8. Coincident events, triggered both with the IACT and the HiSCORE array. The arrival direction is determined with HiSCORE. Events are concentrated within the acceptance of the telescope, see the indicated 4.8 deg dashed FoV circle.

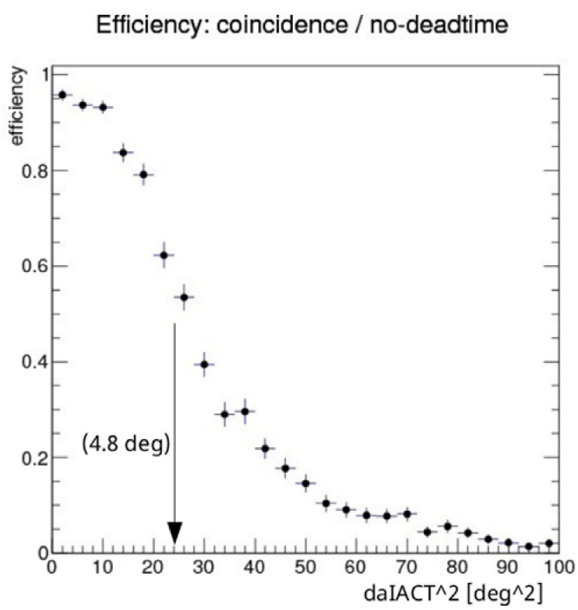

Fig. 9. The efficiency to detect IACT events as function of the angular distance to the center of the telescope.

It includes measurements with current profile amplitudes larger than 0.3 μA and a scan track distance to the pixel center of less than 0.1 deg.

3.2. Joint operation of the IACT and TAIGA-HiSCORE

A main purpose of the TAIGA observatory is a detailed investigation of coincident events, i.e. events that are simultaneously detected with both the TAIGA-HiSCORE array and the TAIGA-IACT. Fig. 8 demonstrates this approach, by plotting on the RA-DEC (right ascension — declination) sky the arrival directions of cosmic ray showers that are detected and fully reconstructed with HiSCORE. Data for 14 TAIGA runs, recorded in the 2017/18 season, and with the IACT operating in precision Crab-nebula tracking mode are shown, selecting HiSCORE events with an IACT trigger within an 1.9 μs time window around the HiSCORE trigger (coincident events). Fig. 9 gives the probability to detect a trigger in the IACT for well reconstructed HiSCORE events as function of $\Delta\alpha$ IACT, the angular distance of the EAS track from the detector pointing (after correction for a 250 μs IACT deadtime). The efficiency is 95% up to $(\sim 3^o)^2$ and 50% at $(4.8^o)^2$ - the radius of the circular telescope FoV.

4. Conclusions

The commissioning of the first stage of the TAIGA gamma observatory should be finished in early of 2020. This TAIGA setup will include 110–120 wide-angle Cherenkov detectors on an area of 1 km^2 and three IACTs. The expected integral sensitivity of this complex for detecting gamma rays with an energy of 100 TeV, assuming a 300-hour observation time per source, will reach approximately 2.5×10^{-13} TeV cm^{-2}s^{-1}. This installation will allow us to prove the experimental potential and the advantage of the hybrid operation of the timing and imaging Cherenkov arrays. As a next step, we intend to construct the full-scale gamma observatory TAIGA with about 1000 timing Cherenkov detectors and up to 16 imaging telescopes distributed over an area of 10 km^2.

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