TeV to PeV gamma-ray astronomy with TAIGA

M. Tluczykont for the TAIGA Collaboration

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Abstract

The gamma-ray sky in the multi-TeV to PeV energy range is so far only poorly covered, and the accelerators of the highest energy Galactic cosmic rays, the Pevatrons, are yet to be identified. Sensitive gamma-ray observations beyond 10 TeV and up to several 100 TeV) are essential for this task, requiring a very large instrumented area (several square kilometers). The international TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma ray Astronomy) experiment aims at covering this energy range using a combination of different complementing detection techniques. Widely spaced wide-angle imaging air Cherenkov telescopes (IACTs) are combined with a Cherenkov light shower front sampling timing array, and with muon particle detectors. A novel hybrid reconstruction technique is used, combining the individual telescope images with the timing and amplitude information from the timing array. This approach allows to maximize the effective area and simultaneously to reach a good gamma-hadron separation at low energies (few TeV). The muon detectors improve the gamma-hadron separation at higher energies. This presentation covers the TAIGA detectors, the hybrid reconstruction technique, and the current status of TAIGA

1 Introduction

More than 150 sources of very high energy (E>100 GeV) gamma rays [1] are known today. The ultra high energy (UHE, E>10 TeV) gamma ray regime is still only poorly covered. Given the quick drop of the flux of astrophysical sources with increasing energy, very large instrumented areas are required to access this regime. A cost effective method to realize large areas and a wide field of view is the shower-front timing technique (also: shower-front sampling), such as realized with the HiSCORE concept [7]. The weak point of such a non-imaging technique is a poor gamma-hadron separation at low energies. This can be compensated by a hybrid combination with a small number of small sized imaging air Cherenkov telescopes (IACTs), such as currently constructed by the TAIGA (Tunka Advanced Instrument for Gamma ray and cosmic-ray Astrophysics) experiment [18, 3, 4]. The hybrid approach combines the timing and imaging techniques using a new hybrid reconstruction (see e.g. [12,] and [13, 14]).

The main astrophysical motivation of TAIGA is the spectroscopic measurement of the cutoff regime of known Galactic sources. Some of these sources might be cosmic-ray accelerators reaching up to the knee energies (around 3 PeV proton energy), i.e. the long-sought Pevatrons. More astrophysical motivations are given in [5, 6].

2 The TAIGA experiment

TAIGA currently consists of 43 fully equipped timing stations (Taiga-HiSCORE), and 1 IACT. A second IACT is under construction. The array is distributed over an area of 0.5 km^2 in the Tunka valley in Siberia (51°48'47.5" N, 103°04'16.3" E, 675 m a.s.l.). The distance between HiSCORE stations ranges from 75 m to 150 m This array is an implementation of the HiSCORE wide-angle timing array concept [7]. A TAIGA-HiSCORE station consists of four 8 inch-photomultiplier tubes (PMTs), each equipped with light a concentrator (Winston cone), resulting in 0.5 m^2 light collection area, and a field of view of 0.6 sr per detector station. The PMTs, voltage-divider, preamplifiers, and light concentrators are installed under a protective plexiglas cover with a heating-wire system (to prevent condensation) in a box with a sliding lid mechanism. All other electronics parts for local station DAQ and slow control are installed in a separate heated electronic box. The DAQ is based on fast GHz signal sampling and operates at a trigger rate of the order of 20 Hz [8]. The PMTs are operated in a high noise environment (night-sky background) at a gain of the order of 10^4. The anode of each PMT is read out and sampled at 2 GHz with a DRS 4-based readout board. An analog summator board is used to split the anode signals. If the analog sum of the anode signals is in excess of a programmable threshold value, a trigger is issued and the anode signals are sampled with the DRS 4 chip. In order to increase the dynamic range for the signal amplitude, also the 5th dynodes are read out. The high-gain channel (anodes) is amplified with a factor of 30, and the low-gain channel (dynodes) with a factor 4. The 9th channel of the DRS 4-based readout board is used for sampling of a central 100 MHz clock which is distributed over optical fiber from the central DAQ. The clock is used by a custom-made time synchronization system and combined with an ethernet-based WhiteRabbit system, providing a central GPS-disciplined Rubidium clock [18]. Upon local trigger, station data are transferred via optical fiber to the central DAQ. Event building is processed offline using the sub-ns precision time-stamps. The optical axis of the stations can be tilted in the north-south direction, therewith varying the part of the sky covered throughout the year. In the northern hemisphere, tilting to the north results in a smaller total sky area covered, but at deeper exposure (about 1000 h per year). Tilting to the south increases the coverage at the expense of exposure per square-degree. During the first two operation seasons, the stations were tilted to the south, allowing observations of the Crab Nebula. In addition to the timing array, a first small IACT (4.75 m dish diameter) was built in 2016 and has taken first data in the last observation season. The TAIGA IACTs consist of a tesselated mirror dish (30 mirrors) on an alt-az mount, equipped with a photomultiplier-tube (PMT) camera. The camera consists of 560 PMTs (XP1911), organized in clusters of up to 28 PMTs. Each cluster is read out separately using a system based on the MAROC chip.

2.1 Performance, and reconstruction quality

Estimations of the sensitivity of TAIGA [15], based on previous simulations [7, 13, 11], result in a sensitivity at the level of $2.5 \cdot 10^{-13}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$ at 100 TeV for a hybrid timing-imaging-array with an instrumented area of $1\,\mathrm{km}^2$ and 3 IACTs.

Parameters used for reconstruction of timing array events are the signal amplitude, charge, and half-rise time, using methods developed for Tunka-133 and HiSCORE [10, 11, 9]. The shower core is first reconstructed with a simple center-of-gravity method, and then refined using a fit of station light densities to a lateral density function. Alternatively, a fit to the amplitude distribution function (ADF) can be performed. A first order direction is obtained from a fit of station arrival times to a plane, followed by more realistic arrival time models, such as a cone-fit, or an analytical model of the arrival times depending on the primary direction, shower core, and shower height. The shower height is also deduced from the slopes of the LDF or ADF fits. As energy estimator, the value of the LDF at a certain distance to the shower core (typically 200 m) is used.

A comparison of real data with MC using the chessboard method (subdivision of arrays) yielded a reconstruction quality within expectations from MC simulations. With an angular resolution of beter than 0.2 deg at a station multiplicity of 10 stations or more, and an energy resolution of the order of typical values for air Cherenkov experiments, reaching 10 % at high energies, the TAIGA performance meets our expectations.

Previously, it was shown that a station time jitter of better than 1 ns (rms) is required in order to reach optimum angular resolution [11]. Two independent station time synchronization methods were successfully employed, and shown to meet these requirements [9, 8, 18].

Reconstruction of IACT events is based on the standard approach using image moment parametrization, as introduced by M. Hillas. More advanced methods based on reconstruction models or neural-net-like approaches will be implemented in the future.

3 This presentation

In this presentation, the status of the TAIGA experiment will be presented, performance studies based on MC simulation and real data will be shown, and comparisons of the TAIGA sensitivity to other experiments will be made.

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