

The HiSCORE Project

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Abstract

A central question of Astroparticle Physics, the origin of cosmic rays, still remains unsolved. HiSCORE (Hundred**i* Square-km Cosmic ORigin Explorer) is a concept for a large-area wide-angle non-imaging air shower detector, addressing this question by searching for cosmic ray pevatrons in the energy range from 10 TeV to few PeV and cosmic rays in the energy range above 100 TeV. In the framework of the Tunka-HiSCORE project, first prototypes have been deployed on the site of the Tunka-133 experiment, where we plan to install an engineering array covering an area of the order of 1 km². On the same site, also imaging and particle detectors are planned, potentially allowing a future hybrid detector system. Here we present the HiSCORE detector principle, its potential for cosmic ray origin search and the status of ongoing activities in the framework of the Tunka-HiSCORE experiment.

Keywords: cosmic rays - Gamma rays - instrumentation - pevatrons.

1 Introduction

Ever since their discovery, cosmic rays have triggered numerous experiments aiming at answering the questions about cosmic ray composition, spectral distribution, and about their origin. Ground-based experiments measure cosmic ray or gamma ray induced air showers via particle or radiation detectors on the ground. The HiSCORE (Hundred**i* Square-km Cosmic ORigin Explorer) concept (Tluczykont et al. 2011), is based on the non-imaging air Cherenkov technique, sampling the Cherenkov radiation emitted by charged air shower particles. Planned as a distributed array of sensitive light collecting stations (0.5 m²), with a wide field of view (0.60-0.84 sr) and a very large instrumented area (up to 100 km²), HiSCORE will cover gamma ray energies above 10 TeV and spectral and composition measure-

ments of cosmic rays from 100 TeV up to the EeV range. The main goal of HiSCORE is to find the cosmic ray pevatrons, that accelerate cosmic rays up to PeV energies, and that are expected to emit gamma rays with a hard spectrum up to several 100 TeV. Air shower measurements at these energies open up several other research possibilities, (Tluczykont et al. 2011).

In the present paper, we describe the HiSCORE detector concept, its potential for a search for cosmic ray pevatrons, and the status of Tunka-HiSCORE, currently (April 2013) in its deployment phase on the site of the Tunka-133 experiment (Berezhev et al. 2012).

2 Detector Concept

The HiSCORE detector is conceived as a distributed array of non-imaging light collecting stations. The array geometry planned for the Tunka-HiSCORE engineering

array is shown in Figure 1.

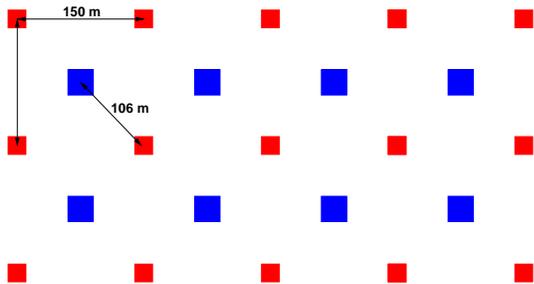


Figure 1: Array layout planned for the Tunka-HiSCORE engineering array. In the standard layout (simulated configuration) four 8 inch PMTs are used per station (red squares). Additional stations with larger PMTs (10 or 11 inch) are envisaged for the engineering array (blue squares).

First results of tests with different array layouts have shown that a graded array with a dense core and decreasing density toward the array edge provides significantly better angular resolution and maximizes the effective area. At the heart of each station, four 8 inch photomultipliers (PMTs) measure the Cherenkov light from secondary air shower particles. Each PMT is equipped with light concentrators (Winston cones) with a half opening angle of 30° , covering a field of view of 0.84 sr . At reconstruction, a quality acceptance cut of 25° results in an effective field of view of 0.6 sr . The total light collection area of one station is 0.5 m^2 . After preamplification, the PMT signals are clipped and summed before passing a comparator. This clipped sum trigger concept prevents false triggers caused by large signal fluctuations from night sky background light or afterpulses. The signal amplitudes are digitized in time using a readout system based on the DRS 4 (Domino Ring Sampler) chip, operated at a sampling frequency of 1 GHz and a depth of $1 \mu\text{s}$. Signal amplitude, timing, rise time, and width of the arrival time distribution are used for the reconstruction of the direction, energy and nature of the primary particle. For a good reconstruction quality, the relative time-synchronization is required to be better than 1 ns between all stations of the distributed array.

During one year, the 0.6 sr viewcone of the detector covers a total area of $\pi \text{ sr}$ for more than 200 h observation time. While this area is much larger than areas typically covered in scans performed by imaging Cherenkov telescope arrays, it is fixed by the location of the experiment. In order to overcome this deficit, we plan to reorient the detector stations after a few years of operation, tilting the detector axis in north-south direction, as illustrated in Figure 2, extending the sky coverage and partly deepening the exposure.

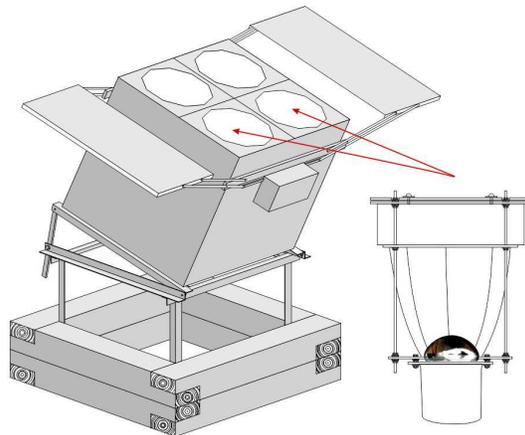


Figure 2: Schematical view of a Tunka-HiSCORE detector station. The tilting mechanism will allow to access a larger fraction of the sky as compared to observations pointing at the zenith alone. Detail (right): Each of the four optical channels consists of a PMT with a light concentrator (Winston cone).

3 Sensitivity

The sensitivity of the HiSCORE standard layout was computed on the basis of a full simulation (Tluczykont et al. 2011) and reconstruction algorithms (Hampf, Tluczykont & Horns 2013). We require a detection at the level of 5 standard deviations and at least 50 gamma rays, leading to the point-source survey sensitivity shown in Figure 3. The blue area corresponds to the sensitivity of the HiSCORE non-imaging array in its standard configuration (8 inch PMTs, 150 m inter-station spacing). The upper edge of the sensitivity range was obtained using conservative assumptions, assuming a ratio α of the solid angles of signal to background regions of unity. The gamma ray survival probabilities are 0.68 for the angular point-source cut, and 0.6 for the hadron rejection cut. More optimistic assumptions were made for the lower bound of the dark shaded area. Here, $\alpha \ll 1$ and the angular cut was relaxed to an efficiency of 1 in the background free regime, above 2 PeV . For direct comparison, the survey sensitivity of CTA (Dubus et al. 2013) is shown as a dashed area, and the LHAASO sensitivity adapted from Cao et al. 2010 with an additional requirement of at least 50 gamma rays is shown as dash-dotted curve. Since the gamma-hadron rejection is poor when using the non-imaging technique alone, the impact of an improvement of the hadron rejection efficiency is significant. For illustration, the cyan area shows the sensitivity range when including an improvement of the hadron rejection by a factor of 10. Such an improvement is realistic when combining the HiSCORE concept with imaging or muon detectors. Imaging detectors have proven

their gamma-hadron separation power up to several 10s of TeV. At higher energies with a rising average number of muons per air shower, muon detectors become more and more efficient for hadron rejection.

HiSCORE will open up the pevatron energy range and allow detailed spectral measurements of the continuation of known gamma-ray sources in the multi-TeV to PeV energy regime. At these energies, the absorption of gamma rays (e^+e^- pair production) in the Interstellar radiation field (ISRF) around 100 TeV and the cosmic microwave background (CMB) around 3 PeV are significant. The level of gamma ray attenuation depends on the density of the radiation fields and the distance of the objects, and can be as low as few percent. Moreover, the density of the CMB being known, the absorption expected at PeV energies from the CMB might open up a new method for distance estimation using gamma ray observations.

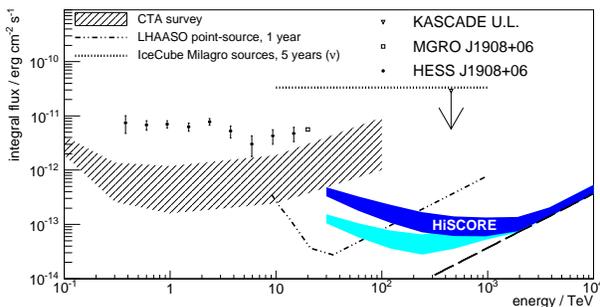


Figure 3: HiSCORE sensitivity as compared to data on MGRO J1908+06 from Milagro (Abdo et al. 2007) and H.E.S.S. (Aharonian et al. 2009), and the sensitivity of IceCube to neutrinos from Milagro sources (Gonzalez-Garcia et al. 2009). Also given are an upper limit from KASCADE (Antoni et al. 2004), and sensitivities for experiments CTA (Dubus et al. 2013) and LHAASO (Cao et al. 2010).

Recently, the IceCube collaboration reported the detection of 28 neutrinos (e.g. Whitehorn 2013), in excess of the atmospheric and prompt neutrino expectations, but compatible with a pevatron like spectrum. These findings are a strong additional motivation for our search for Galactic cosmic ray pevatrons.

4 Status of Tunka-HiSCORE

4.1 Detector components

Different solutions are available for the individual detector components. The photomultipliers (PMTs) are required to sustain a high level of noise and to operate at a gain level of $10^4 - 10^5$. Currently, 8 inch PMTs fulfilling these requirements are available from EMI, ElectronTubes and Hamamatsu (including a mod-

ified 6-stage prototype). The Winston cones are assembled similarly to the construction of a wine barrel in stripes along the optical axis, using reflective sheets of ALANOD 4300UP material. In the currently operating prototypes (April 2013), standard Tunka-133 preamplifiers are in use. An analog summator for the station trigger system (see Section 2) was tested in laboratory and in the field. In its final implementation, the trigger board includes clipping and triggering. Further three trigger solutions are available: FADC trigger onboard the Tunka-133 readout, FPGA based trigger on-board the White Rabbit board, and amplitude discrimination on-board the DRS4 evaluation board. All three alternative triggers use the analog sum as input. Two readout systems are in operation: the standard FADC readout (200 MHz) used by Tunka-133, and the DRS4 evaluation board (1 GHz).

4.2 Prototype results

The first Tunka-HiSCORE prototype station (2 PMT channels) was deployed in the Tunka valley in April 2012. Two additional detector stations were deployed in October 2012. Joint operation with Tunka since then provided first cross-calibration data and experience with components. The Tunka-133 FADC and the DRS4 evaluation board readout were tested in parallel in Spring 2013. Runs with varying thresholds were performed in order to measure the integral trigger rate as a function of the trigger threshold (Epimakhov et al. 2013). As can be seen in Figure 4, the expectations for the cosmic ray branch and the noise wall can be reproduced.

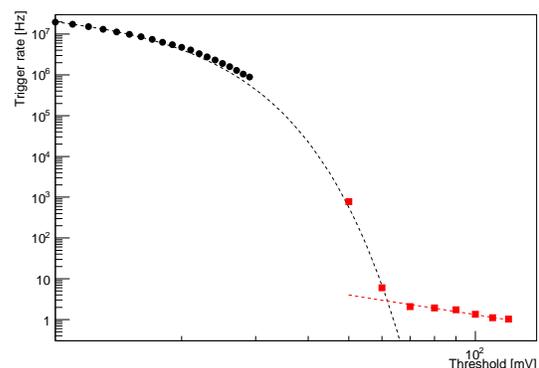


Figure 4: The trigger rate (station 4) as a function of the trigger threshold, measured with the DRS4 evaluation board in Spring 2013 (Epimakhov et al. 2013). *Red squares:* dead-time corrected data, *red dashed line:* cosmic ray triggers, *black points:* estimation of NSB triggers from baseline fluctuations, *black dashed curve:* the NSB noise wall.

Similar measurements using the FADC readout yield consistent results (Wischnewski et al. 2013). An effective quantum efficiency of 0.06 could be derived from the latter measurement. This translates into a threshold for Cherenkov light detection of 0.6 photons/m², which corresponds to an energy threshold of slightly less than 100 TeV when using the FADC trigger (25 ns discriminator response). The final system will have a faster response. We also plan to use faster preamplifiers, larger PMTs, and geo-magnetic shielding for the PMTs, ultimately lowering the energy threshold of the HiSCORE stations to the 10–30 TeV energy range. Tests of the White Rabbit (WR) system show that the time precision and stability at the 200 picos level measured in the laboratory can be reproduced at the Tunka site (Brückner et al. 2013). The observed time difference distribution of WR-tagged events is consistent with the observation of air showers with the given viewing angle of the Tunka-HiSCORE stations (Wischnewski et al. 2013).

5 Conclusion and Outlook

Using the new large-area wide-angle non-imaging HiSCORE detector concept, we plan to access the pevatron gamma ray energy range (10 TeV – several 100 TeV) and also address cosmic ray physics around the knee region. The Tunka-HiSCORE experiment has started the deployment of detector stations in the Tunka valley in Siberia. 3 prototype stations are in operation, and further 6 stations will be deployed by the end of 2013. The construction of an engineering array that will cover an area of 1 km² is planned for the near future. Different alternatives for the station design (8 inch or 10 inch PMTs) and for the array layout (graded array) are considered. A combination with small imaging telescopes (2-3 m² mirrors, 10° field of view) is planned to complement the Tunka-HiSCORE array. Furthermore, the installation of muon detectors and fluorescence telescopes at the Tunka site is considered for the future, improving gamma hadron separation and cosmic ray composition, and leading to a multi component extended air shower array in the Tunka valley in Siberia.

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DISCUSSION (from memory)

QUESTIONER: At these high energies, gamma rays are absorbed in low energy radiation fields. How can you expect sources in the 100 TeV energy range?

MARTIN TLUCZYKONT: The strength of the attenuation depends on the location of the object within our Galaxy. An object located at the far side of

the Galaxy behind the Galactic center was shown (Moskalenko et al. 2006) to be absorbed at the 50% level. Any other object located closer to the sun, or off-center the Galactic disk, will be less absorbed, down to only few %.