ARTICLE IN PRESS

Nuclear Inst. and Methods in Physics Research, A xxx (xxxx) xxx

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Cherenkov EAS arrays in the Tunka astrophysical center: From Tunka-133 to the TAIGA gamma and cosmic ray hybrid detector

L. Kuzmichev [a,*], I. Astapov [i], P. Bezyazeekov [b], A. Borodin [j], M. Brückner [h], N. Budnev [b], A. Chiavassa [d], O. Gress [b], T. Gress [b], O. Grishin [b], A. Dyachok [b], O. Fedorov [b], A. Gafarov [b], A. Garmash [k], V. Grebenyuk [j,o], A. Grinyuk [j], D. Horns [f], N. Kalmykov [a], Y. Kazarina [b], V. Kindin [i], V. Kiryuhin [b], P. Kirilenko [k,l], R. Kokoulin [i], K. Kompaniets [i], E. Korosteleva [a], V. Kozhin [a], E. Kravchenko [k,l], A. Kryukov [a], A. Lagutin [n], V. Lenok [b], B. Lubsandorzhiev [c], N. Lubsandorzhiev [a], R. Mirgazov [b], R. Mirzoyan [e,b], R. Monkhoev [b], E. Osipova [a], A. Pakharukov [b], A. Pan [j], M. Panasyuk [a], L. Pankov [b], A. Petrukhin [i], V. Poleschuk [b], M. Popesku [m], E. Popova [a], A. Porelli [h], E. Postnikov [a], V. Prosin [a], V. Ptuskin [g], A. Pushnin [b], R. Raikin [n], G. Rubtsov [c], E. Ryabov [b], Y. Sagan [j,o], V. Samoliga [b], Yu. Semeney [b], A. Silaev [a], A. Silaev Jr. [a], A. Sidorenkov [c], A. Skurikhin [a], M. Slunecka [j], A. Sokolov [k,l], C. Spiering [h], L. Sveshnikova [a], V. Tabolenko [b], B. Tarashansky [b], A. Tkachenko [j], L. Tkachev [j,o], M. Tluczykont [f], N. Ushakov [c], D. Voronin [c], R. Wischnewski [h], A. Zagorodnikov [b], D. Zhurov [b], V. Zurbanov [b], I. Yashin [i]

[a] *Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia*
[b] *Institute of Applied Physics ISU, Irkutsk, Russia*
[c] *Institute for Nuclear Research of RAN, Moscow, Russia*
[d] *Dipartimento di Fisica Generale Universiteta di Torino and INFN, Torino, Italy*
[e] *Max-Planck-Institute for Physics, Munich, Germany*
[f] *Institut fur Experimentalphysik, University of Hamburg, Germany*
[g] *IZMIRAN, Moscow, Russia*
[h] *DESY, Zeuthen, Germany*
[i] *NRNU MEPhI, Moscow, Russia*
[j] *JINR, Dubna, Russia*
[k] *Novosibirsk State University, NSU, Novosibirsk, Russia*
[l] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*
[m] *ISS, Bucharest, Romania*
[n] *Altai State University, Barnaul, Russia*
[o] *Dubna State University, Dubna, Russia*

ARTICLE INFO

Keywords:
Cosmic rays
Gamma-ray astronomy
EAS Cherenkov light array
Energy spectrum
IACT

ABSTRACT

One of the most informative methods of cosmic ray studies is the detection of Cherenkov light from extensive air showers (EAS). The primary energy reconstruction is possible by using the Earth's atmosphere as a huge calorimeter. The EAS Cherenkov light array Tunka-133, with ~3 km^2 geometrical area, is taking data since 2009. Tunka-133 is located in the Tunka Astrophysical Center at ~50 km west of Lake Baikal. This array allows us to perform a detailed study of the energy spectrum and the mass composition in the energy range from $6 \cdot 10^{15}$ eV to 10^{18} eV. Most of the ongoing efforts are focused on the construction of the first stage of the detector TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy). The latter is designed for the study of gamma rays and charged cosmic rays in the energy range of 10^{13} eV–10^{18} eV. The TAIGA prototype will consist of ~100 wide angle timing Cherenkov stations (TAIGA-HiSCORE) and three IACTs deployed over an area of ~1 km^2. The installation of the array is planned to be finished in 2019 while the data-taking can start already during the commissioning phase. The joint reconstruction of energy, direction, and core position of the imaging and non-imaging detectors will allow us to increase the distance between the IACTs up to 800 m,

* Corresponding author.
E-mail address: kuz@dec1.sinp.msu.ru (L. Kuzmichev).

https://doi.org/10.1016/j.nima.2019.01.056
Received 8 November 2018; Received in revised form 17 January 2019; Accepted 17 January 2019
Available online xxxx
0168-9002/

therefore providing a low-cost, highly sensitive detector. The relatively low cost together with the high sensitivity for energies ≥30–50 TeV make this pioneering technique very attractive for exploring galactic PeVatrons and cosmic rays. In addition to the Cherenkov light detectors we intend to deploy surface and underground muon detectors over an area of 1 km^2 with a total area of about 1000 m^2. The results of the first season of coincident operation of the first ∼4 m diameter IACT with an aperture of ∼10° with 30 stations of TAIGA-HiSCORE will be presented.

1. Introduction

The progress in understanding the nature of sources of high-energy cosmic rays from our Galaxy and from the Metagalaxy is exploiting three complimentary avenues:

1. the study of secondary gamma quanta, produced by cosmic rays (CR) in the vicinity of the source, where particles are accelerated;
2. high-energy neutrinos produced by hadronic interactions are studied by neutrino telescopes;
3. the precise determination of the energy spectrum, mass composition and anisotropy of CRs by detailed measurements of all EAS parameters;

In the past, the Tunka Astrophysical Center in the Tunka Valley (50 km from Lake Baikal) was solely devoted to this third approach. Recently we have also began to address gamma-ray astronomy (i.e. the hitherto most successful way to find individual sources of CRs) and have started to deploy a gamma-ray observatory at the Tunka site. The name of this observatory is TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy). In this paper we describe briefly the main results of the CR experiment in Tunka Valley, present the current status and results of the TAIGA experiment and discuss plans for future TAIGA extensions.

2. The main results of VHE ($\geq 10^{15}$ eV) CR experiments in the Tunka Valley

At present, three arrays to study VHE($\leq 10^{15}$ eV charged CRs are operated at the Tunka site: Tunka-133 [1], Tunka-REX [2] and Tunka-Grande [3]. Their measurement of the energy spectrum and mass composition is important in order to understand the acceleration limit of the Galactic CR sources and the transition from Galactic to extragalactic CR. Tunka-133 consists of 175 optical detectors with a hemispherical photocathode of 20 cm diameter, spaced over an area of 3 km^2.

Our methods of EAS parameter reconstruction have been presented in several papers [1,4]. The Cherenkov light array Tunka-133 was operated on clear moonless nights between October and early April from 2009. Here we present the data of 7 seasons of array operation. The total time of data acquisition is 2200 h.

The differential energy spectrum is shown in Fig. 1 along with the previous spectrum of Tunka-25 [5]. The spectrum of Tunka-133 shows a number of features which indicate deviations from the power law. One can interpret the picture as a much more complicated behavior than a power law (or multiply broken power law). The power law description can be used only for small parts of the spectrum — not more than half an order of magnitude. At an energy of about $2 \cdot 10^{16}$ eV the power law index changes from $\gamma = 3.28 \pm 0.01$ to $\gamma = 2.99 \pm 0.01$. Points of the spectrum are consistent with such an index till $E_0 = 3 \cdot 10^{17}$ eV. The spectrum becomes much steeper with $\gamma = 3.34 \pm 0.09$ above the last point (the second "knee").

3. High energy gamma-ray astronomy and the TAIGA project

For the energy range of gamma quanta above 30 TeV there are a number of fundamental questions which presently have no answers. Among these there is the question on the sources of Galactic cosmic rays with energies around 1 PeV, the energy region approximately adjoining the classical knee in the all-particle energy spectrum.

The TAIGA installation is designed to study gamma radiation and the charged cosmic rays in the energy range of 10^{13} — 10^{18} eV [6]. The observatory will include a network of wide field of view (0.6 sr) timing Cherenkov light stations, named TAIGA-HiSCORE [7,8] (High Sensitivity Cosmic Origin Explorer), and up to 16 imaging atmospheric Cherenkov telescopes, covering an area of 10 km^2. The capabilities of these Cherenkov arrays are enhanced by muon detectors (TAIGA-Muon) with a total coverage of 2000 m^2, distributed over an area of 1 km^2. The advantage of a few IACTs added to the wide-angle timing array is their better gamma/hadron separation by image parameter information, while core position, direction and energy can be better reconstructed by the timing array. Combination of information from both components gives a superior result compared to the performance of each single component. The detection sensitivity for local sources of a 10 km^2 observatory in the energy range of 30–200 TeV is expected to be $5 \cdot 10^{-14}$ TeV cm^{-2} s^{-1} for 500 h of observation or 10 detected events.

4. The TAIGA current status and main results

4.1. TAIGA-HiSCORE

As of August 2018, the prototype of TAIGA consists of 54 TAIGA-HiSCORE stations and one IACT. 54 optical stations are distributed in a regular grid over a surface area of 0.5 km^2 with an inter-station spacing of 106 m. All stations are tilted into the southern direction by 25° to increase the time for the study of gamma-quanta fluxes from the first test object — the Crab Nebula. Each optical station contains four large area PMTs with 20 or 25 cm diameter, namely EMI ET9352KB, or Hamamatsu R5912 and R7081. Each PMT has a Winston cone with 0.4 m diameter and a 30° viewing angle (field of view is ∼ 0.6 sr). Each station is connected with the DAQ center by a fiber optic cable for data transfer and synchronization. The synchronization stability of the optical stations reaches about 0.2 ns. Precision calibration is achieved by external light sources. Signals from anode and intermediate dynode are digitized with a step of 0.5 ns by a special board based on the DRS-4 chip. A more detailed description of DAQ and synchronization systems is given in [9]. Reconstruction of shower parameters was performed using algorithms developed for the Tunka-133 array [1,4]. In simulations the reconstruction method reproduced all the steps of data processing. 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 [10]. The accuracy of the reconstruction procedure was checked on MC simulation as well as with experimental data. The latter are presented in [11,12] (chess-board method).

Approximately twice per month during the season of 2016–2107, the installation detected signals from the CATS (Cloud Aerosol Transport System) — lidar onboard the ISS [13]. The lidar operates at a wavelength of 532 nm with a frequency of 4 kHz. On March 23, 2017 the signal from the lidar was also registered with the MASTER optical telescope [14], located at a distance of 500 m from the center of the installation. Comparison of the angular position of events with maximum amplitudes in HiSCORE stations, restored with calibrated delays, and the position of the point of maximum brightness according to the MASTER telescope showed that the absolute angular accuracy of the array is not worse than 0.1° [15].

Our preliminary spectrum is compared (Fig. 2) with the results of previous experiments in the Tunka Valley, as well as with the results of the balloon experiment ATIC-2 [16], the satellite experiment NUCLEON [17] and a new experimental spectrum obtained by the HAWC [18] experiment in Mexico. In Fig. 2 intensity of cosmic rays is multiplied by E$^{2.7}$ not by E^3 as in Fig. 1, because for energy smaller than $3 \cdot 10^{15}$ eV power index of energy spectrum is about −2.7.

Please cite this article as: L. Kuzmichev, I. Astapov, P. Bezyazeekov et al., Cherenkov EAS arrays in the Tunka astrophysical center: From Tunka-133 to the TAIGA gamma and cosmic ray hybrid detector, Nuclear Inst. and Methods in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.01.056.

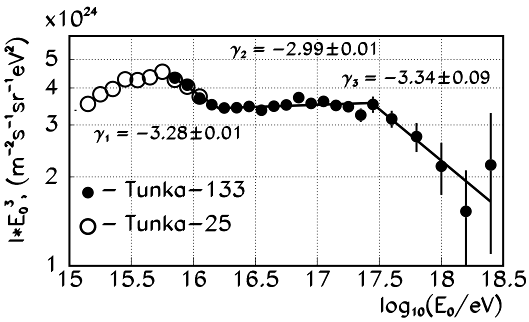

Fig. 1. Differential primary cosmic ray energy spectrum.

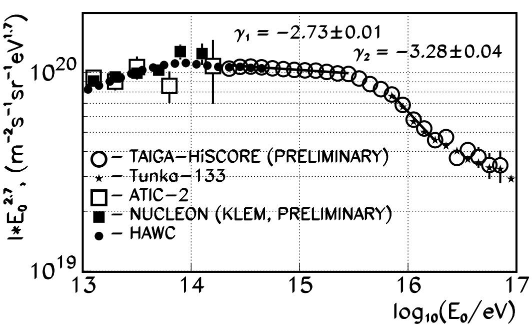

Fig. 2. The energy spectrum of primary cosmic rays from the data of the TAIGA-HiSCORE array in comparison with other experiments.

4.2. TAIGA-IACT

The imaging atmospheric Cherenkov telescope has an optical design of the Davis-Cotton type with 29 mirrors, each of 60 cm diameter and a focal length of 4.75 m. The imaging camera comprises 560 PMTs of XP1911 type (Photonis) of 19 mm diameter. The FOV of the camera is 9.6° (each pixel has an aperture 0.36°), with a Point Spread Function (PSF) of 0.07°. The CCD-camera Prosilica GC1380 is installed at a distance of 1 m from the telescope optical axis on the mirror dish. The CCD-camera is used for checking the telescope pointing direction. It has 1360 × 1024 pixels resolution and 31.4°×23.6° field of view. Each axis of the telescope is equipped with a Phytron hybrid stepper motor, a 17-bit shaft encoder and end-of-zone switches connected to the PhyMOTION control unit.

The camera consists of identical clusters, each based on 28 PMTs. The basis of the cluster electronics is a 64-channel ASIC MAROC-3. Each channel includes a preamplifier with adjustable gain, a charge sensitive amplifier and a comparator with adjustable threshold. This chip has a multiplexed analog output signal which is proportional to the input charge. The chip is connected to a 12-bit external ADC. The signal from each PMT is split and fed into 2 MAROC-3 channels with a gains difference of 30. This results in a full dynamic range of 3000 photoelectrons.

After the installation of the shaft encoder on the axis in September 2017, the commissioning of the TAIGA-IACT telescope tracking system was started and first source observations were performed in October 2017. In the 2017–2018 season telescope pointing accuracy was $\sim 0.05^o$ for the corrected observations in March (mostly Mrk 421) and around 0.1 ° for the other runs (Crab Nebula and Mrk 421) [19].

The first test sources selected for observation were the Crab Nebula and Mrk-421. Previously it was planned that these sources would be observed for 120 h. Unfortunately due to bad weather and a number of technical problems it was possible to observe these sources only for about 25 h.

The search for joint events recorded by the telescope and a TAIGA-HiSCORE array was carried out while tracking the Crab Nebula [20]. On

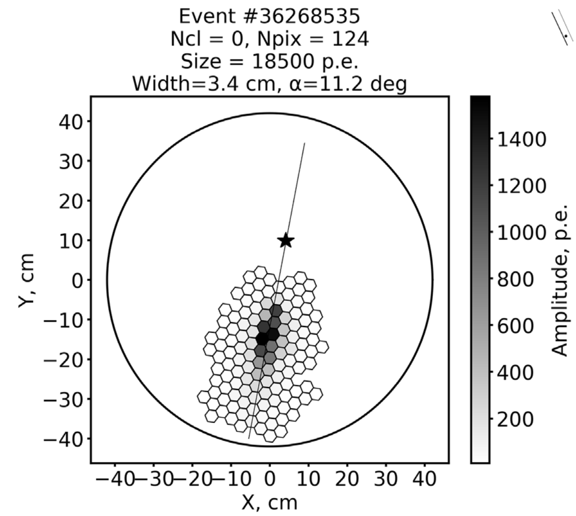

Fig. 3. Example of a hadron-like joint event. Parameters of image: Size = 18500 p.e., Width = 0.4°, Alfa = 11°.

Fig. 3 an example of a joint hadron-like event detected by the telescope and TAIGA-HiSCORE is presented. The asterisk on this figure is the projection of the EAS core position on the plane of the telescope camera with the introduction of the scaling factor: R_p (cm) / R_c (cm) = 1500, (R_p is the distance from telescope to EAS core position, R_c — distance from camera center and asterisk). The line on the picture is directed to the EAS core. For events coming from the source to which the telescope is oriented, the line connecting the projection of the EAS axis and the center of gravity of the image should cross the center of the camera. The same event was detected by 15 stations of the TAIGA-HiSCORE array: E = 840 TeV, $\theta = 30.1°$, $\phi = 33.6°$, R_p = 134 m, the angle between the direction of the shower, reconstructed by timing array and direction of the source is $\psi = 0.47°$.

17,000 joint events with an image size ≥ 60 p.e. were selected. These events were detected by the first 30 stations of the TAIGA-HiSCORE array, with an area of 0.25 km^2. Fig. 4 A shows the width distributions for joint events with size between 1000 and 3000 pe. The thin solid line indicates the MC simulations for a similar sample of events, obtained from experiment. The thick solid line at this figure is the Width distributions for gamma rays for the mentioned sample. Selecting 60% of gamma-events (Width ≤ 0.17°, Alfa ≤ 15°) we suppressed hadron background by a factor of ∼ 100. With such cuts we have a Q-factor of 5 which is in agreement with the Q-factor, used in calculations of the TAIGA sensitivity to local gamma-ray sources [21]. After applying Width (≤ 0.18°), Alfa (≤ 15°) and Dist.(≤ 2.5°) cuts, there remain 35 events with $\Psi \leq 4°$, Ψ — being the angle between direction of showers, reconstructed by TAIGA-HiSCORE and the direction of the Crab Nebula. The Ψ^2distributions of these hybrid events after cuts is presented on Fig. 4 B. For 14 of these events, with energies between 45 and 60 TeV, $\Psi \leq 1°$. These events may be considered as candidates for first gamma-like events selected by the hybrid approach.

5. Conclusions

A unique complex of installations for the study of high-energy cosmic rays is being constructed at the Tunka Astrophysical Center. The complex includes the Tunka-133 array detecting EAS Cherenkov light, Tunka-REX for detection of EAS radio emission and the Tunka-Grande array for detection of charged particles (electrons and muons). The joint operation of these arrays opens new opportunities for studying the cosmic radiation with energies more than 10^{16} eV.

The first significant steps towards completing the gamma-ray observatory TAIGA have been performed.

Please cite this article as: L. Kuzmichev, I. Astapov, P. Bezyazeekov et al., Cherenkov EAS arrays in the Tunka astrophysical center: From Tunka-133 to the TAIGA gamma and cosmic ray hybrid detector, Nuclear Inst. and Methods in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.01.056.

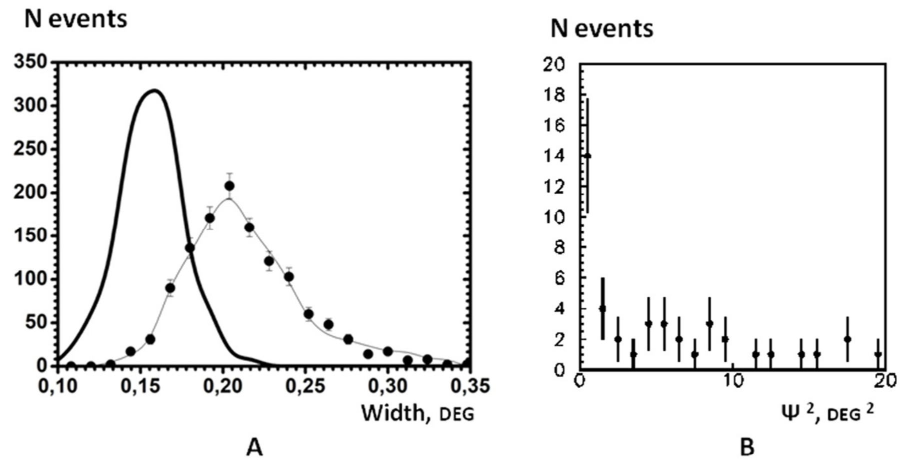

Fig. 4. A:Image Width distribution for joint events. Solid circles — experiment. Thin solid line — MC (cosmic rays), thick solid line — MC (gamma quanta). B: Ψ^2 distribution for hybrid event after cuts (see text for details).

The first seasons of operation of the TAIGA-HiSCORE and first TAIGA-IACT demonstrated good performance of the installation and showed yet preliminary but interesting results. During the winter season 2018–2019 the TAIGA configuration will include 54 operational wide angle stations arranged over an area of 0.5 km^2, and one IACT. During the next year it is planned to finish deployment of the first stage of TAIGA with 110 TAIGA-HiSCORE stations and 3 IACTs on an area of 1 km^2. The expected integral sensitivity for 300 h of source observation (about 2–3 seasons of operation) in the range 30–200 TeV is about $5{\cdot}10^{-13}$ TeV cm^{-2} s^{-1}.

Acknowledgments

This work was supported by the Russian Federation Ministry of Education and Science (projects 14.593.21.0005 (Tunka shared core facilities, unique identificator RFMEFI59317X0005), 3.10131.2017/NM, 2017-14-595-0001-003, 3.9678.2017/8.9, 3.904.2017/4.6, 3.5917.2017/BCh, 3.6787.2017/7.8, 3.5939.2017/8.9, 1.6790.2017/7.8), the Russian Foundation for Basic Research (Grants 16-02-00738, 16-02-01103, 16-32-00329, 17-02-00905, 16-29-13035), the German Helmholtz Association (grant HRJRG-303), the DFG, Germany (grant TL 51-3) and the European Union's Horizon 2020 program under grant agreement No. 653477.

References

[1] S. Berezhnev, et al., (Tunka Collaboration), NIM A 692 (2012) 98.
[2] P.A. Bezyazeekov, et al., (Tunka-REX Collaboration), J. Cosmol. Astropart. Phys. 01 (2016) 052.
[3] R. Monhoev, et al., (Tunka Collaboration), Bull. Russ. Acad. Sci. Phys. 81 (2017) 504.
[4] V.V. Prosin, et al., (Tunka Collaboration), NIM A 756 (2014) 94.
[5] N. Budnev, et al., (Tunka Collaboration), Astropart. Phys. 50 (2013) 18–25.
[6] N. Budnev, et al., (TAIGA Collaboration), J. Phys. Conf. Ser. 718 (2016) 052006.
[7] M. Tluczykont, et al., Adv. Space Res. 48 (2011) 1935–1941.
[8] M. Tluczykont, et al., Astropart. Phys. 56 (2014) 42.
[9] O. Gress, et al., (TAIGA Collaboration), NIM A 845 (2017) 367.
[10] L. Kuzmichev, et al., (TAIGA Collaboration), EPJ Web Conf. 145 (2017) 01001.
[11] M. Tluczykont, et al., (TAIGA Collaboration), Proceedings of RICAP16 6th Roma International Conference on Astroparticle Physics. EPJ Web Conferences.
[12] A. Porelli, et al., (TAIGA Collaboration), Proceeding of ECRS 2014, J. Phys. Conf. Ser. 632 (2015) 012041.
[13] http://cats.gsfc.nasa.gov/.
[14] V. Lipunov, et al., Adv. Astron. 2010 (2010) 349171.
[15] A. Porelli, et al., (TAIGA Collaboration), Pos, ICRC2017, vol. 754.
[16] A. Panov, et al., Bull. Russ. Acad. Sci. Phys. 73 (5) (2011) 564.
[17] N. Gorbunov, et al., (Nucleon Collaboration) arXiv:1809.05333.
[18] Alfaro, et al., (HAWC Collaboration), Phys. Rev. D 96 (2017) 122001.
[19] D. Zhurov, et al., (TAIGA Collaboration) Report at 26-th ECRS, Barnaul, 2018. To be published in J. Phys. Conf. Ser..
[20] L. Sveshnikova, et al., Report at 26-th ECRS, Barnaul, 2018. To be pulished in Bull. Russ. Acad. Sci. Phys. (2019).
[21] L. Kuzmichev, et al., (TAIGA Collaboration), Phys. At. Nuclei 81 (4) (2018) 506.

Please cite this article as: L. Kuzmichev, I. Astapov, P. Bezyazeekov et al., Cherenkov EAS arrays in the Tunka astrophysical center: From Tunka-133 to the TAIGA gamma and cosmic ray hybrid detector, Nuclear Inst. and Methods in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.01.056.