Tunka-Grande and TAIGA-Muon scintillation arrays: status and prospects

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Abstract. The Tunka-Grande and TAIGA-Muon arrays are the part of a single experimental complex, which also includes the Tunka-133 and TAIGA-HiSCORE (High Sensitivity COSmic Rays and gamma Explorer) wide-angle Cherenkov arrays, TAIGA-IACT array (Imaging
Atmospheric Cherenkov Telescope) and Tunka-Rex radio antennas array (Tunka Radio Extension). This complex is located in the Tunka Valley (Buryatia Republic, Russia), 50 km from Lake Baikal. It is aimed at investigating the energy spectrum and mass composition of charged cosmic rays in the energy range 100 TeV - 1000 PeV, searching for diffuse gamma rays above 100 TeV and studying local sources of gamma rays with energies above 30 TeV.

This report outlines 3 key points. The first is a description of the Tunka-Grande and TAIGA-Muon scintillation arrays. The second part presents preliminary results of the search for diffuse gamma rays with energies above 50 PeV according to the Tunka-Grande data. The third part is devoted to the prospects of the search for diffuse gamma rays with energies above 100 TeV using the TAIGA-Muon array.

1. Introduction
The study of charged cosmic rays and primary gamma rays of high and ultrahigh energies is a great interest from the point of view of understanding the mechanisms and nature of their origin, which is the most important task of the modern astrophysics. In this case, registration of such radiation is carried out using only the method currently possible, based on the property of primary particles to generate a cascade of secondary particles in the Earth's atmosphere, the so-called extensive air shower (EAS). When such the shower develops, a large number of components arise in it. The electron-photon, hadron, and muon components, as well as the accompanying Cherenkov, ionization, and radio emission reach the Earth's level of observation. All of these components can be used to determine the properties of primary cosmic radiation. Nowadays, the simultaneous detection and the study of many parameters of EAS with the help of so-called hybrid systems, such as the experimental complex is located in the Tunka Valley, is of major importance.

Astrophysical research in the Tunka Valley has begun in 1993 and for many years was aimed at the study of charged cosmic rays, which continues to this day in the following operating experiments: since 2009 at the Tunka-133 array [1], since 2012 at the Tunka-Rex array [2] and since 2015 at the Tunka-Grande array [3,4]. However, primary charged particles are significantly affected by galactic and intergalactic magnetic fields, which lead to a strong distortion of their trajectories and, as a result, to the loss of any information about their origin. In many ways, this reason has contributed to the rapid development in the world of experimental gamma-ray astronomy in recent years. Indeed, since gamma rays are electrically neutral, they can be used as a pointer to the astrophysical objects in which they were formed. But their flux is low compared to the total flux of cosmic radiation and from the experimental point of view, the problem arises of their separation from the background events of high-energy charged particles. To solve this non-trivial task, the work began on the creation of the TAIGA-HiSCORE [5,6], TAIGA-IACT [7] and TAIGA-Muon arrays in 2012, 2017 and 2019 respectively. All 3 arrays are currently combined in a single project called the TAIGA gamma observatory (Tunka Advanced Instrument for cosmic ray and Gamma Astronomy).

2. Tunka-Grande
The Tunka-Grande set-up is designed to detect the charged component of EAS and is presented as an array of scintillation counters combined in 19 stations on an area of 1 km². Each of them consists of 2 parts: surface and underground. The first detects all EAS charged particles at the level of array and consists of 12 counters on area is about 8 m², while the second, consisting of 8 counters with a total area is about 5 m², is located under a layer of soil ~ 1.5 m thick and is designed to separate muon EAS components. Both parts are in close proximity to each other. The scintillation counter is a duralumin case in the form of a truncated pyramid whose inside face is covered by a thin diffusely reflecting layer of white enamel. Inside the case there is the NE102A plastic scintillator in the form of a flat plate 800 mm × 800 mm × 40 mm in size and the Philips XP-3462 photomultiplier tube (PMT). The geometry of the counter allows to attain high uniformity both in the amplitude of signals and in the time a signal arrives at the output of the PMT with respect to that of a charged particle passing through the scintillator. Two counters at each station have additional PMTs whose amplification factor is at 10
times lower than the standard one, ensuring a wide range of linearity in the measured signals. This type of counters is also currently used in the NEVOD-EAS [8] experiment, and has previously been successfully used in the KASCADE-Grande [9] and EAS-TOP [10] experiments.

One of the tasks of the Tunka-Grande array is studying of the energy spectrum and mass composition of charged cosmic rays in the energy range of 50 PeV - 1000 PeV along with the Tunka-133 and Tunka-Rex arrays. The search for the possible presence of diffuse gamma rays of these energies in the total flux of cosmic radiation determines another important problem. Indeed, a number of models and theories predict the flux of gamma rays of high and ultrahigh energies that can be detected. The first experiments to researching of them were begun more than half a century ago, but despite of the efforts of the numerous researching groups, astrophysical photons with energies above 400 TeV have not yet been discovered and only restrictions on their flux are currently established. So, in the energy range of about 300 TeV-50 PeV, the EAS-TOP [11], CASA-MIA [12] and KASCADE [13] experiments was made a significant contribution to the research. In the region of about 10 PeV-300 PeV, the EAS-MSU [14] and KASCADE-Grande [13] experiments, in the region of more than 1000 PeV, the Haverah Park [15], AGASA [16], Yakutsk [17], Pierre Auger [18], and Telescope Array [19] experiments. According to the data from 2015 to 2017, the Tunka-Grande array also received a preliminary limit on the flux [20] (figure 1). The main idea of separating primary gamma rays from the background of charged cosmic rays is studying the muon component of showers because the number of muons in a shower from gamma rays is an order of magnitude smaller than in the hadron one.

**Figure 1.** Flux fraction of gamma rays in relation to cosmic rays flux by the KASCADE-Grande, KASCADE, CASA-MIA and Tunka-Grande experiments.

Based on the data from the Tunka-Grande array, the obtained restrictions on the flux of diffuse gamma rays are still slightly worse than the restrictions obtained in the EAS-MSU and KASCADE-Grande experiments. This can be explained by the fact that the analysis used experimental data for a relatively short period. But the Tunka-Grande array continues data collection in non-stop mode, has a high potential and in the coming years, the upper limits in the energy range of 50 PeV-500 PeV will be significantly improved.
3. TAIGA-Muon
In terms of solving cosmic rays physics and gamma rays astronomy problems, the main drawback of the optical stations and telescopes of the TAIGA-HiSCORE and TAIGA-IACT arrays is that they conduct observations only on clear moonless nights. Thus, their effective working time does not exceed 10% of the calendar year. Also, telescopes of the TAIGA-IACT array have a rather small viewing angle of $\sim 10^\circ$. On this basis, in 2019, in addition to the Tunka-Grande, work began on the construction of the TAIGA-Muon scintillation array with an estimated total detector area of about 2000 m$^2$. It is worth noting that the operation of the new array in a wide range of zenith angles of arrival of primary particles will not only determine the flux of diffuse gamma rays, but also find local areas with an excess of them. Subsequently, upon detection, such areas will be studied in detail using of the TAIGA-HiSCORE and TAIGA – IACT arrays. Till now, 3 clusters of the TAIGA-Muon array are deployed (figure 2).

![Figure 2. Outer look of one TAIGA-Muon cluster (a) and positions of TAIGA-Muon clusters - red circles and Tunka-Grande stations - blue squares (b).](image)

Each cluster has 8 surface scintillation counters to detect all EAS charged particles at the level of array and 8 underground to detect the muon component. At the same time, the counters are geometrically arranged in pairs: surface just above the underground. All 8 pairs are placed along the perimeter of the square with a side of 5 m. The distance between adjacent pairs is 1 m. It should be noted that the cluster design does not provide direct access to the underground part, the soil thickness over which is $\sim 1.6$ m. Each TAIGA-Muon counter [21] consists of a duralumin case, inside of which there are 4 triangular scintillation plates with a variable thickness of 10 -20 mm based on polystyrene with the addition of 1.5% p-Terphenyl and 0.01% POPOP, shifter with a cross section of 5 mm $\times$ 20 mm (acrylic glass with BBQ dye), diffuse reflectors and PMT FEU-85. An increase in the thickness of the scintillation plates to the periphery of the counters and the using of optical fiber plates make it possible to achieve acceptable uniformity of signal amplitudes from different parts of the counters. The total area of the counter is 1 m$^2$.

4. Conclusion
The Tunka-Grande and TAIGA-MUON arrays have high potential and in the coming years it will allow:

1. To obtain qualitative results on the energy spectrum and the mass composition of charged cosmic rays in the energy range of 50-1000 PeV by the Tunka-133 and Tunka-Rex arrays collaboration.
2. To significantly improve the upper limits of diffuse gamma rays flux in the 50-500 PeV range.
3. To search for diffuse gamma rays with an energy of more than 100 Tev.
4. To isolate local regions with an excess of gamma rays with energy above 100 Tev and begin to examine them in detail along with the TAIGA-HiSCORE and TAIGA-IACT arrays.

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