

# Simulation of the Tunka-Grande, TAIGA-Muon and TAIGA-HiSCORE arrays for a search of astrophysical gamma quanta with energy above 100 TeV

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**Abstract.** In the paper we present our simulation strategy of the Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays in the light of the problem of separation astrophysical high-energy gamma rays from the cosmic ray background. The paper contains a description of our simulation method, based on Geant4 and CORSIKA codes. We also present the prospect of future research with TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) with using the simulation results.

## 1. Introduction

The study of gamma-ray fluxes generated in the vicinity of galactic and metagalactic sources of high-energy cosmic rays has proved to be the most effective way to analyze their nature. We can observe these rays both from separate galactic or extragalactic sources and diffuse gamma-ray background.

The search for astrophysical gamma rays with energies above 100 TeV is carried out using ground-based detectors of extensive air showers (EAS). EASs are generated by interaction of astrophysical particles with the Earth's atmosphere and consist of fluxes of secondary particles (like hadrons and leptons) and various types of electromagnetic radiation. The main difficulty, in this case, is a separation of EASs initiated by gamma quanta from the general background. The most effective but expensive separation method for EAS type identification is to study the shape of the EAS image using IACT telescopes. An alternative and less costly approach is based on studying the muon component of the EAS since the number of muons in the EAS generated by gamma quanta is an order of magnitude less than in a hadronic one.

At the same time, the search for high-energy gamma rays by studying the muon component is possible using detector arrays of the TAIGA experimental complex [1]. This complex located in the Tunka Valley ( $\varphi = 51^\circ 48' 47,5'' N$ ,  $\lambda = 103^\circ 04' 16,3'' E$ ,  $h = 675 \text{ m a.s.l.}$ ) and is capable of searching for high-energy gamma rays from data on the EAS muon component using the Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays [2, 3, 4]. The positions of the stations (or clusters, if we talk about TAIGA-Muon) around TAIGA observatory are mapped in figure 1.

The low-threshold Cherenkov array TAIGA-HiSCORE efficiently records events starting from energy of 100 TeV and has a reliable method for reconstructing the EAS parameters and the primary particle energy. The data from the Tunka-Grande array ( $E \approx 30 \text{ PeV}$ ), containing information on the electron and muon components of the EAS, are an essential addition to the data from the TAIGA-HiSCORE. To expand the scintillation experiment to the low-energy region, a large-area TAIGA-Muon network of muon detectors is being deployed.

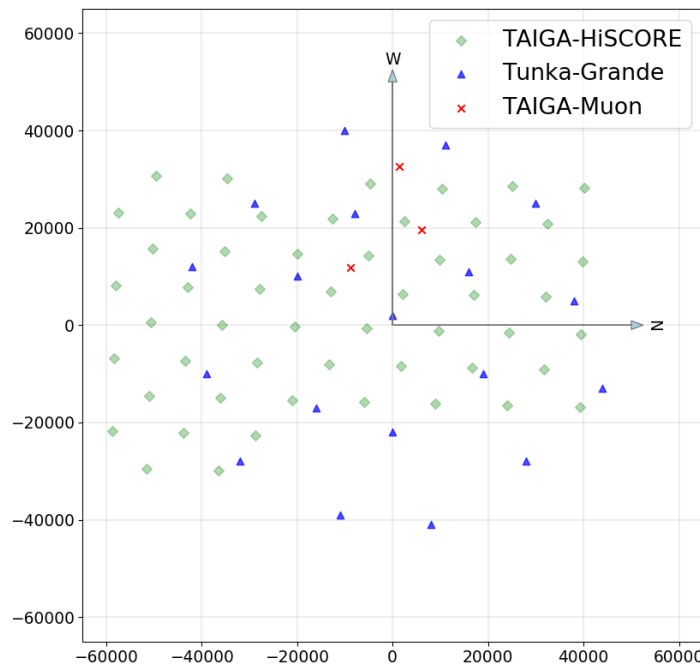
The joint analysis of the Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE data is capable of providing more versatile information both on the energy spectrum and mass composition of cosmic rays, and on the search for astrophysical gamma quanta.

## 2. Simulation strategy

The simulation of the Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays allows evaluating the effectiveness of the proposed separation method. Also, it could solve technical problems inevitable when organizing the joint operation of detector arrays of various types.

For the simulation of the joint operation of Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays we created a “bank” or of artificial EASs by use of CORSIKA toolkit [5, 6] (based on the QGSJET-II-04 high-energy hadron interaction model [7]). EASs were generated by various primary particles such as gamma, proton, and iron at different angles of incidence and with energies in the range from 100 TeV to 1 PeV. The main feature of this bank is that for any individual EAS

information is stored both on all secondary particles detected at the observation level and on Cherenkov radiation.



**Figure 1.** Locations of the arrays relative to each other on the TAIGA site: 54 TAIGA-HiSCORE stations, 19 Tunka-Grande stations, and 3 TAIGA-Muon clusters.

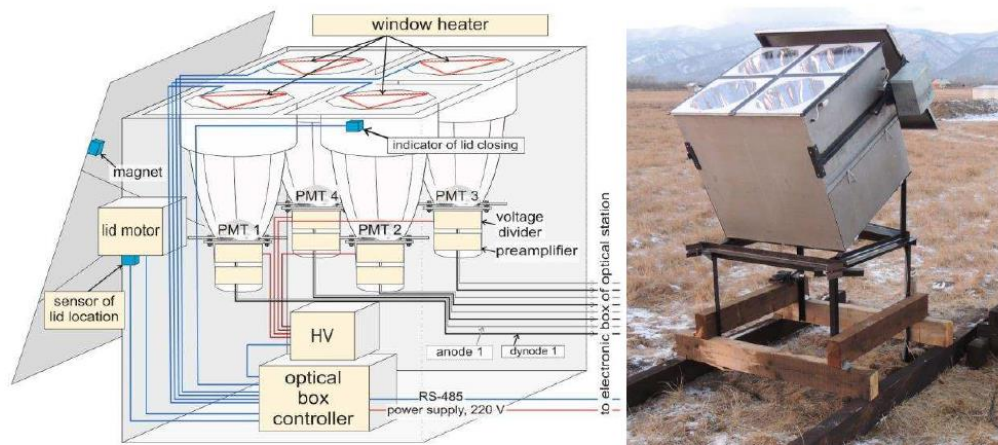
The simulation of the response of the TAIGA-HiSCORE array to Cherenkov radiation was carried out with the CORSIKA [5] simulations of EAS. The simulation of the Tunka-Grande and TAIGA-Muon arrays response to EASs was carried out by Geant4 toolkit [8]. We provide the full description of each simulation further in the text. All necessary calculations were performed on HPC-cluster «*Akademik V.M. Matrosov*» [9].

### 2.1. TAIGA-HiSCORE simulation.

TAIGA-HiSCORE is a wide-angle non-imaging air-Cherenkov array with an area of around 0.6 km<sup>2</sup>. The TAIGA-HiSCORE array consists of a number of optical stations in the form of metal boxes (size of 1×1×1 m<sup>3</sup>) with remotely-operated protection lid (against sunlight, atmospheric precipitations, and dust) and various electronic systems. Each of these metal boxes contains the optical module, consisted of four photomultipliers with Winston cone (PMT could be EMI ET9352KB, or Hamamatsu R5912 and R7081) [4]. To increase the observation time for the Crab Nebula, all stations are tilted southward by 25°. An area of the light-collecting surface of the station is 0.5 m<sup>2</sup>, a viewing angle is 0.6 sr. The full layout of the ordinary TAIGA-HiSCORE station is imaged in figure 2.

The simulation of TAIGA-HiSCORE was carried out using CORSIKA tools at the stage of artificial EAS creation. We use special extension for CORSIKA enabling Cherenkov light production – IACT/ATMO package [10]. The package allows setting an array of Imaging Atmospheric Cherenkov Telescope (IACT) in the form of abstract spheres on a detection plane. This

implementation allows us to set geometry and positions of detectors and specify an area where an EAS axis can hit the detection plane ensuring that the EAS axis hits a coverage area of the IACT array. The TAIGA-HiSCORE array model was set via CORSIKA in the form of 54 spherical detectors with a diameter of 1 m, corresponding to the characteristic size of optical modules of each of the 54 TAIGA-HiSCORE stations located at distances corresponding to real ones. It should be noted that at the time of summer 2020, there were already 83 stations at the TAIGA complex, but the new stations have not yet been included in the simulation.



**Figure 2.** General TAIGA-HiSCORE design and photo of a single station deployed on the territory of the TAIGA complex.

One of the main features of modeling EAS Cherenkov radiation in CORSIKA is that during the EAS development photons are not generated one by one but in the form of photon bunches, where the maximum bunch size is specified by the user in the input file. The condition for the detection of the photon bunch is the intersection of the particle trajectory of the surface of the sphere. At the CORSIKA observation level, a rectangular grid is set up. And only bunches that fall into the cells attached to this sphere (number of cells depends on the position of the detector in  $z$  – coordinate as well as its distance from EAS axis) at the observation level are checked for the intersection with the sphere.

The information about each detected photon is recorded in a machine- and compiler-independent, flexible data format, termed *eventio* [10]. Output is written to file with the ‘.iact’ extension, and has the following information about photon bunches: coordinates in the detector coordinate system in the horizontal plane passing through the center of the sphere, coordinates of the directional unit vector, as well as the wavelength of a photon bunch, the number of photons, the time of arrival of at the CORSIKA observation level, emission height above sea level.

The spherical model of the detector used in CORSIKA, of course, does not provide the most reliable simulation of TAIGA-HiSCORE station. To simulate the operation of the station, it is necessary to sort the detected photons. Primarily, it is necessary to take into account the geometric dimensions of the station (the area of the light-collecting surface of the station is  $0.5 \text{ m}^2$  [4]), its inclination (all optical stations are tilted southward by  $25^\circ$ ), as well as its limited viewing angle –  $30^\circ$ . This scheme is illustrated in figure 3.

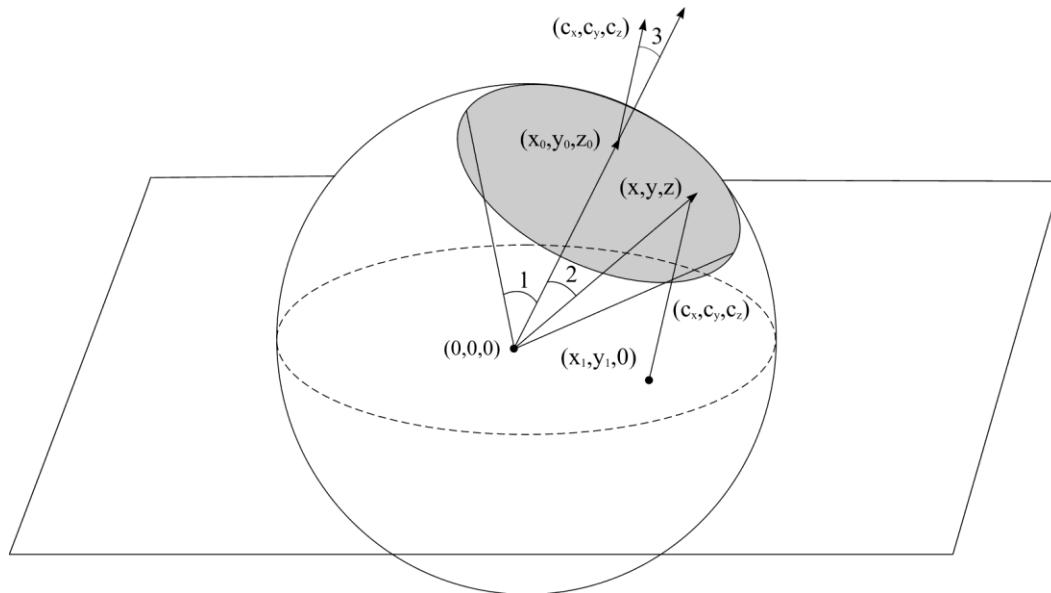
In order to select the detected photons while taking into account the parameters of the TAIGA-HiSCORE optical station, it is necessary to reconstruct points of intersection of the photon bunches with the detector surface. This problem is reduced to finding the points of intersection of the sphere and the straight line describing the trajectory of the photon bunch. The line equation is derived by using the bunch coordinates and its direction vector. The equation of the sphere in the detector

coordinate system has a simple form like  $x^2+y^2+z^2 = 2500$ . Solving the resulting system of equations, we obtain two points, one of which must be discarded (the upper was always chosen as the intersection point).

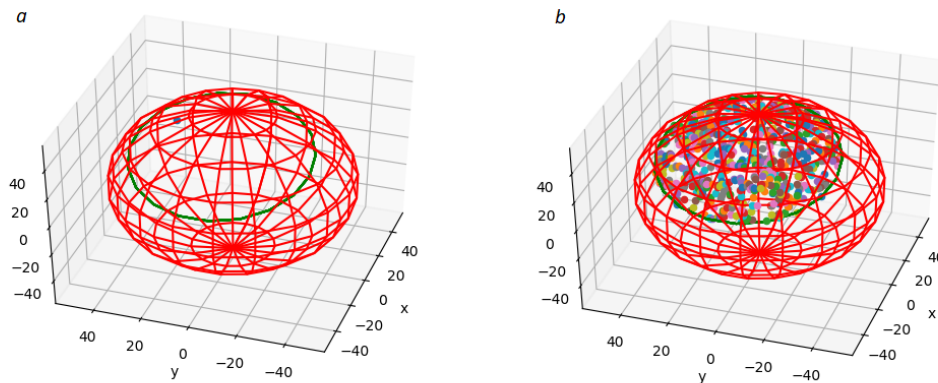
The light collection area of the station is represented as follows. The point is marked on the sphere, which in the spherical coordinate system of the detector has a zenith angle of  $25^\circ$  and an azimuth angle of  $180^\circ$ , which ensures the "tilt" and southbound direction of the light-collecting surface. Then, around this point, the surface of  $0.5 \text{ m}^2$  is "cutout". The aperture of the cone cutting out a surface of such the area on a sphere with a radius of 50 cm is 94 degrees. Thus, the condition for the photon bunch hitting the required surface is  $\angle 2 \leq 94/2 = 47^\circ$  and  $\angle 2$  is the angle formed by vectors  $(x, y, z)$  and  $(x_0, y_0, z_0)$ .

Also, it is necessary to take into account the limited viewing angle of the optical station:  $0^\circ \leq \theta \leq 30^\circ$ . To take this into account, only those photon bunches are selected whose directional vector makes an angle  $\angle 3 \leq 30^\circ$  with the vector  $(x_0, y_0, z_0)$ .

The photon-selection program is written in Python 3. The result of its work for EASs with different directions of arrival of the primary particle is presented in figure 4. In the future, it is planned to simulate the response of TAIGA-HiSCORE using the experimentally measured angular sensitivity of an optical module.



**Figure 3.**  $(x, y, z)$  – coordinates of intersection point of photon bunch's and sphere,  $(x_0, y_0, z_0)$  – vector pointing direction of light-collecting surface of model of the HiSCORE station,  $(x_i, y_i)$  – coordinates of photon bunch's in detection plane,  $(cx, cy, cz)$  – directional vector of trajectory of photon bunch's.



**Figure 4.** The points of intersection with the sphere of those bunches that satisfy the condition for the angle of incidence ( $\angle 3 \leq 30^\circ$ ). EASs with a primary particle having a zenith angle of  $45^\circ$  and an azimuthal angle of  $90^\circ$  (a) and  $180^\circ$  (b) were used.

## 2.2. Tunka-Grande and TAIGA-Muon simulation.

Geant4 toolkit [8] was chosen for simulating of the Tunka-Grande and the TAIGA-Muon scintillation arrays response to EAS. This toolkit, based on the Monte-Carlo method, was created by the staff of the European Organization for Nuclear Research (CERN) to simulate the passage of elementary particles (radiation) through matter using Monte Carlo methods [11].

Geant4 is known for its great practical potential. It allows you to create a complete spatial geometry of detectors (or arrays of them) and simulate their interaction with various types of elementary particle. In this case, for all components of the detectors, you can set a specific chemical composition or describe the materials from which they are made [12]. It permits the collection of varied data such as the path traveled by a particle, its momentum or energy at a given point or, in case of occurring, its decay. Geant4 also can provide the visualization of the simulation.

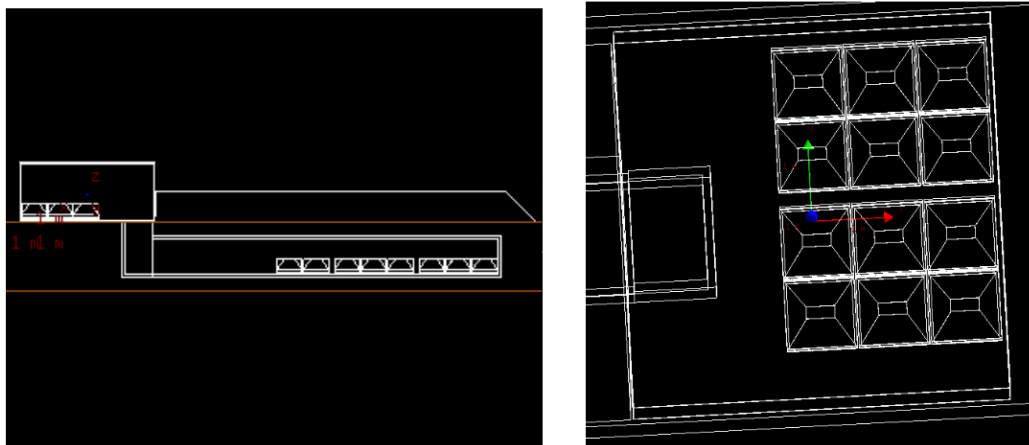
Using the Geant4 toolkit, we developed the code that simulates the response of the scintillation arrays and their interaction with particles. The main task was to describe the geometry and composition of all detectors as accurately as possible, while maintaining the speed of the software, and to obtain information on the energy deposition of the detected particles for each individual detector. *FTFP\_BERT* physics list was used for both codes, which is proper for high energy physics calorimetry [13].

The simulation of the scintillation detectors should be performed according to the following scheme. First, information about particles in artificial EASs, simulated through CORSIKA and contained in special binaries, is converted into the text format that Geant4 needs for input. We can do it through the special program linked with the CORSIKA libraries (by means of COAST tool [14]). Second, the data in a new format, containing information about the location, energy, momentum, and type of particles, is given to the Geant4-based code for launch. At the launch of this code the particles start from a certain height (1–2 m) relative to the certain zero level, near that the array stations are located. Then, at the output of the code, we receive information about an energy deposit and a number of detected particles per their sort at every detector of each array during any EAS, when secondary particles of EAS interact with array detectors.

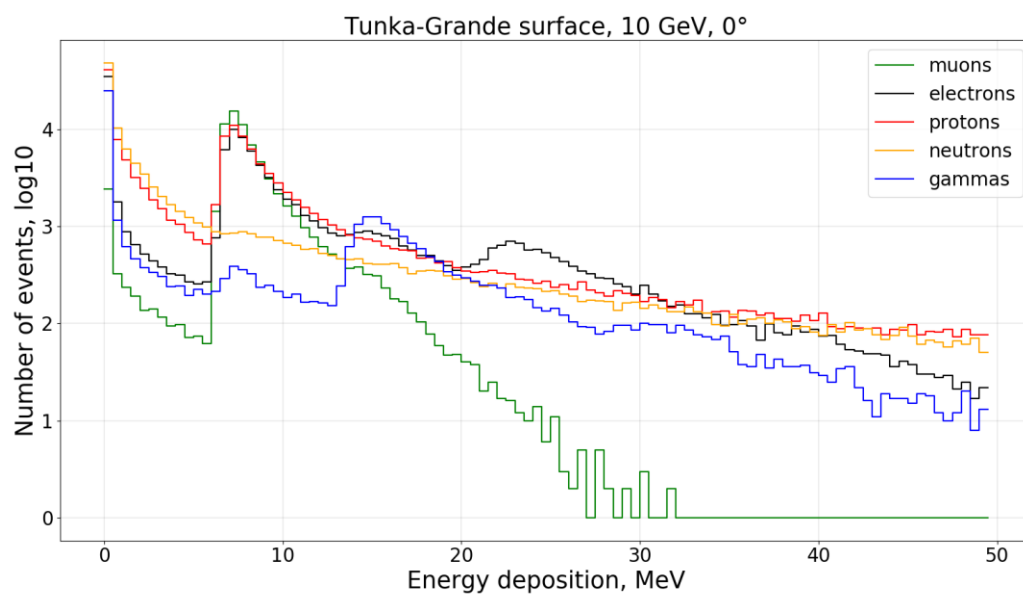
The Tunka-Grande code contains full geometry of all 19 stations of this array, and its computer model is as close to reality as possible. For each station, the complete geometric model is provided: a concrete underground tunnel with 8 lined counters, a soil embankment 1.5 meters thick above it, and a ground-based tin box with 12 counters inside. Each Tunka-Grande 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 is a NE102A plastic scintillator in the form of a flat plate  $800 \text{ mm} \times 800 \text{ mm} \times 40 \text{ mm}$  in size, and a PMT Philips XP-3462 [2].

In the Tunka-Grande code all counters themselves are defined by complex geometric volumes with all needed “chemistry” and materials, completely imitating the components of the real counter. Vector visualization of a single Tunka-Grande station can be seen in figure 5. The sample of energy deposit spectra obtained for Tunka-Grande is illustrated in figures 6 and 7, for  $0^\circ$ . It can be seen that the shape of the spectrum is dependent on the particle type. Also, figure 7 shows, that only muon particles could effectively reach underground detectors.

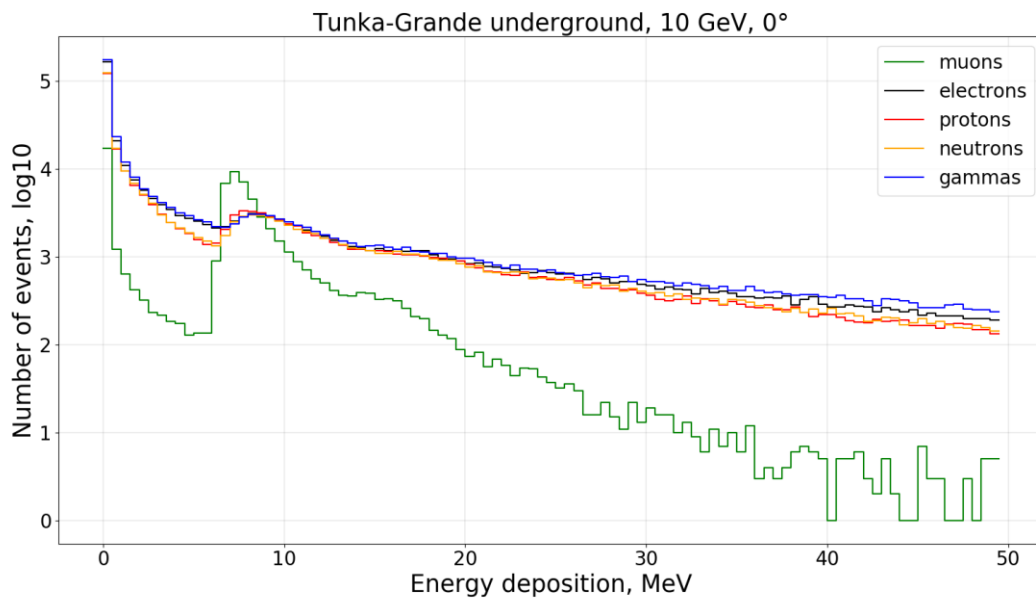


**Figure 5.** Geant4 visualization of a single Tunka-Grande station. *Left:* the entire station in a side view. *Right:* the ground-based counters from a top view.

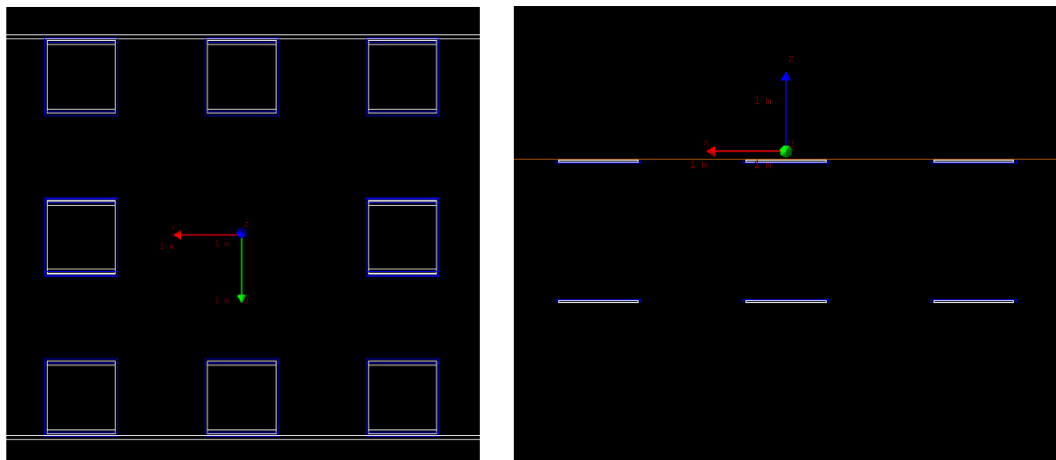


**Figure 6.** Simulated energy deposit spectrum from the Tunka-Grande ground-based counters for vertically incident particles and with the energy about 10 GeV.





**Figure 7.** Simulated energy deposit spectrum from the Tunka-Grande underground counters for vertically incident particles and with the energy about 10 GeV.



**Figure 8.** Geant4 visualization of a single TAIGA-Muon cluster. *Left:* the entire cluster in a top view. *Right:* the ground-based counters from a side view.

The TAIGA-Muon code simulates the first cluster of the array (1 of 3) launched in test mode. The virtual cluster, like the real one, contains 8 counters on the surface and 8 counters underground at a depth of 1.6 m. The structure of the TAIGA-Muon scintillation counter is much more complicated than the Tunka-Grande counter. Each TAIGA-Muon counter 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, a shifter with a cross-section of 5 mm × 20 mm (acrylic glass with BBQ dye), diffuse reflectors and PMT FEU-85 [3]. However, when trying to use such geometry and composition in the simulations directly, there were performance issues during the interactions of the detectors with particles.

In order to maintain the performance of the code, it was decided to simplify the model. Therefore, the model of the TAIGA-Muon counter repeats the size of the real one without taking into account its



internal structure and represents a flat square scintillator “pancake” 1 cm thick and with a total area of the counter about 1 m<sup>2</sup>. The use of such a simplification affects the reliability of the results of the simulation, which are very different from those expected in a real experiment. In general, TAIGA-Muon code is ready only like a prototype or as a “skeleton” of future correct implementation and still requires additional development. Visualization of a single TAIGA-Muon cluster is given in figure 8.

### 3. Conclusion

Using the Geant4 and CORSIKA tools, we created programs and code to simulate the Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE. With their help, we will carry out a preliminary test of the method for separating gamma quant events using data of EAS muon and electronic component. For this, in each EAS event from our “EAS bank”, we will found the muon density (according to the data of underground detectors) and the electron density (according to the data of ground-based detectors) and then will calculate their ratio. The distribution of these ratios by energy per type of cosmic primary particle, which initiates EAS, will show could we clearly separate gamma rays from charged cosmic rays. In addition, analysis of the TAIGA-HiSCORE simulation with Cherenkov radiation interactions might also provide some useful information on the method.

However, the reliability of the analysis requires more statistics and data from the modeling of a larger number of artificial EAS. Also, when the Geant4 code of Tunka-Grande performs very well, further development of the TAIGA-Muon code is planned to get realistic simulation, and some upgrades for the TAIGA-HiSCORE simulation model is planned as well. The future results of these tests and simulations are planned to be integrated into the general frame of the detection and reconstruction of real EASs at the TAIGA experiment.

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