

Geant4 simulation of the Tunka-Grande experiment

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Abstract. The Tunka-Grande array is 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-IAC T array (Imaging Atmospheric Cherenkov Telescope) and TAGA-MUON scintillation array. This complex is located in the Tunka Valley (Buryatia Republic, Russia), 50 km from Lake Baikal. It is designed to study the



energy spectrum and the mass composition of charged cosmic rays in the energy range 100 TeV - 1000 PeV, to search for diffuse gamma rays above 100 TeV and to study local sources of gamma rays with energies above 30 TeV.

This report outlines 3 key points. The first is the description of the Tunka-Grande scintillation array. The second one presents the computer simulation strategy of the Tunka Grande array based on the Geant4 software. The third one is devoted to the prospects for future research in the field of cosmic ray physics and gamma-ray astronomy using simulation results.

1. Introduction

The study of the charged cosmic rays and cosmic gamma rays of high and ultrahigh energies has a great interest for understanding the mechanisms and nature of their origin, which is the most important task of modern astrophysics. The 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 EAS 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 level of observation in Earth's atmosphere. All of these components can be used to reconstruct the properties of primary cosmic radiation. Nowadays, the simultaneous detection and the study of many parameters of EAS with the help of the ground base hybrid systems, similar to the experimental complex 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] and since 2015 at the Tunka-Grande array [2,3]. It is known that primary charged particles are deflected by galactic and intergalactic magnetic fields, that lead to the loss of any information about direction to the origin. In many ways, this reason has contributed to the rapid development 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 produced. However, since the gamma-ray flux is low compared to the cosmic ray flux, the problem arises, how to separate gamma-quanta from the background events caused by high-energy charged particles. To solve this non-trivial task, the work began on the creation of the TAIGA-HiSCORE [4,5], TAIGA-IACT [6] and TAIGA-Muon [7] arrays in 2012, 2017 and 2019 respectively. All 3 arrays are currently combined in a single project, the TAIGA gamma observatory (Tunka Advanced Instrument for cosmic ray and Gamma Astronomy).

The computer simulation for ground based particle detector arrays is an important part of their operation. This makes possible study of regularities in the EAS development, accurate finding of the EAS characteristics dependence on the cosmic radiation parameters, an evaluation of the efficiency of EAS detection and the quality of the EAS parameters reconstruction, as well as the development of experimental methods for elemental separation of primary particles. In the standard procedure, detectors operation are simulated in two steps. At the first, the development of an EAS is simulated, at the second, the detector response to passage of elementary particles is simulated as well. To solve these tasks at the Tunka-Grande array, the CORSIKA [8] and Geant4 [9,10] packages were chosen as the software.

2. Experimental set-up

The Tunka-Grande 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 0.5 km². Each of them consists of two parts: surface and underground. The first detects all EAS charged particles at the level of the array and consists of 12 counters covering an area of about 8 m², while the second, consisting of 8 counters with a total area of about 5 m², is located under a layer of soil ~ 1.5 m thick and is designed to detect muon EAS component. Both parts are near each other. The scintillation counter has the form of a truncated pyramid which inner surface 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 $800\text{ mm} \times 800\text{ mm} \times 40\text{ mm}$ in size and the Philips XP-3462 photomultiplier tube (PMT). The geometry of the counter allows attaining 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 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 [11] experiment and has previously been successfully used in the KASCADE-Grande [12] and EAS-TOP [13] experiments

The electronics of the station coincides largely with the electronics of the cluster of the Tunka-133 array. Two analog signal adders are optional. The 12 local scintillation counters that constitute a surface part are divided into two halves and are connected to two separate adders. The stations can send information about both the arrival of the «external» trigger signal from the nearest cluster of the Tunka-133 array and the arrival of the signal from the «local» trigger of the surface part. The local trigger generation condition is the signal from a relativistic particle at the output of each adder within 500 ns. The count rate of one station in the «local» trigger mode is about 10 Hz.

The aim of the Tunka-Grande array is studying of the energy spectrum and mass composition of charged cosmic rays in the energy range of 10 - 1000 PeV, as well as to search for diffuse gamma-rays in the same energy range.

3. Geant4 model of Tunka-Grande array

The Geant4 toolkit for the simulation of the particles passage through matter is chosen to simulate the Tunka-Grande array response to EAS. This package is known for its great practical potential and makes it possible to create an accurate computer model of detectors (or their arrays) and simulate the interaction of various types of elementary particles with detector elements.

In the computer model of the Tunka-Grande array, the complete geometry of all 19 stations is set and it is as close to reality as possible. For each station, the structure and chemical composition are described in detail: a concrete underground tunnel with 8 counters, a layer of soil $\sim 1.5\text{ m}$ above it and a surface box with 12 counters inside (figure 1). High-speed software and hardware allow processing of EASes from the CORSIKA packages up to 1000 PeV.

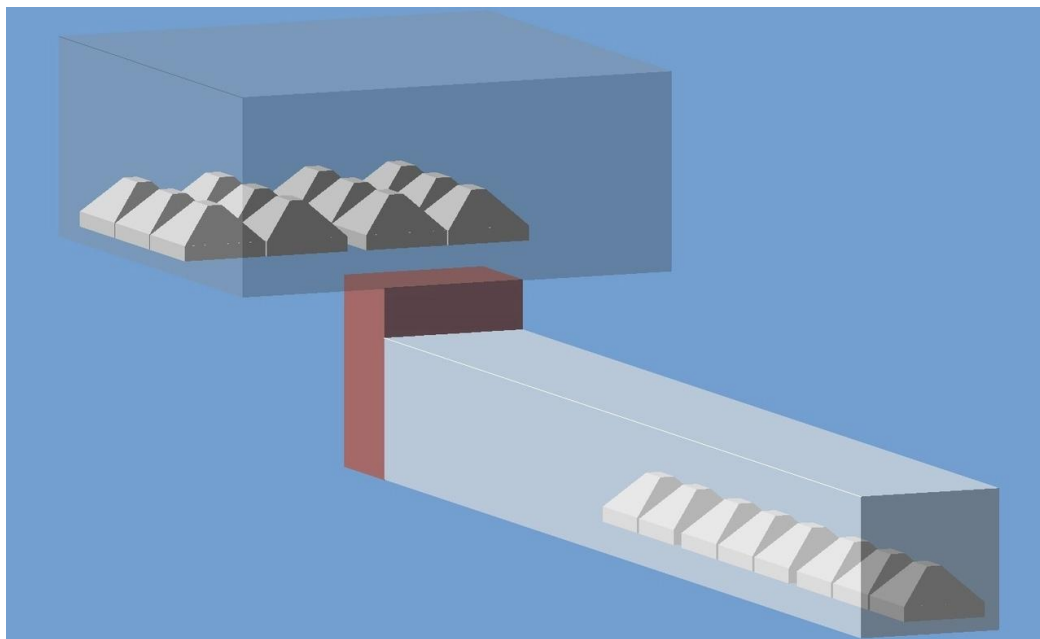


Figure 1. Schematic representation of the Tunka-Grande station.

An example of the energy deposit spectra in the surface part of a station during the passage of single vertical particles different types through the detector is shown in figure 2. The figure presents the simulated energy spectra released in the detector by electrons (red line), muons (black), photons (blue) and neutrons (green) with initial energy of 1 GeV. The pattern appears rather familiar as reflecting the processes of the ionization and radiation energy losses. It should be noted that model does not provide for the operation of the read-out electronics of Tunka-Grande array. The final analysis of the response of scintillation counters, in addition to fluctuations of energy losses in the scintillation plate, provides for the inhomogeneity of the light collection in the duralumin case [14].

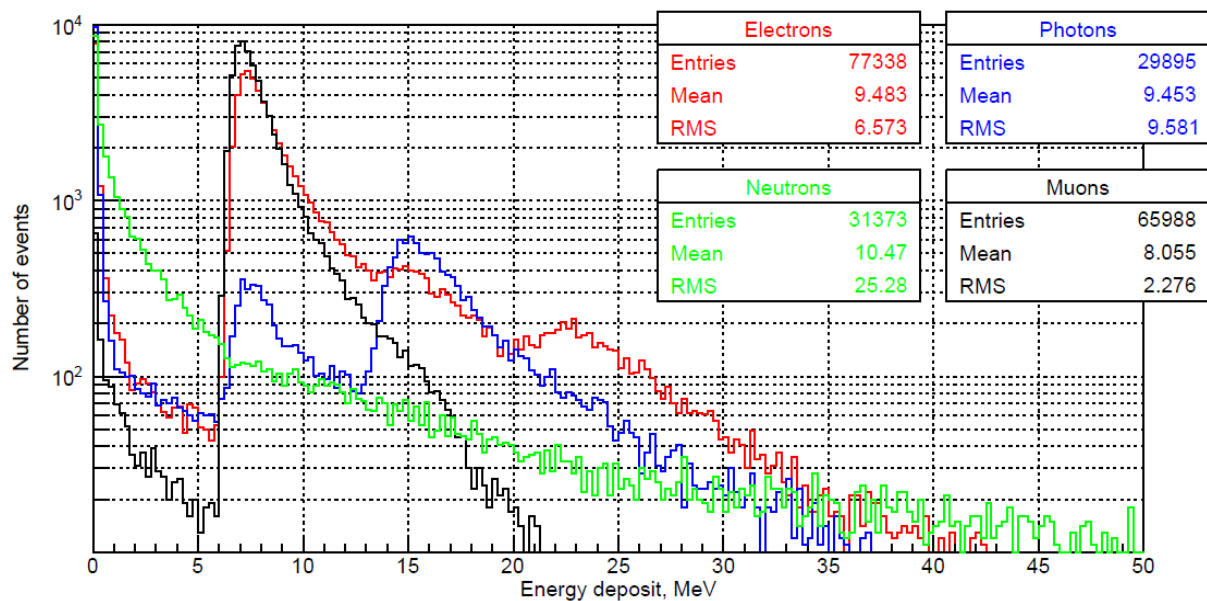


Figure 2. Simulated energy deposit spectra for vertically incident particles.

4. Conclusion

Continuous progress of computer technologies, techniques and simulation environments provides an opportunity to improve the quality of information obtained in various experiments. The creation of the Geant4 model of the Tunka-Grande array is of great importance and in the near future, together with the use of CORSIKA package, it will allow:

1. To improve significantly the accuracy of measurement of EAS and primary cosmic radiation parameters and thus to obtain qualitative results on the energy spectrum of cosmic rays in the energy range of 10-1000 PeV.
2. To develop a technique for the primary particles identification. This will make possible the detailed study of the cosmic rays elemental composition and begin the search for diffuse gamma-rays in the energy range of 10-1000 PeV.

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