

The HERO (High-Energy Ray Observatory) simulation

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The main goal of the High-Energy Ray Observatory (HERO) mission is to perform direct measurements of very high energy cosmic ray. Measurements will concern the following scientific goals: detailed study of charge composition of CR in knee region, studies of the energy spectra of Galactic and extragalactic CR, search for signatures of dark matter particles. HERO is planned to be launched onboard a heavy satellite. This experiment is based on the application of a wide aperture ($>2\pi$) deep ($\sim 5\lambda$) ionization calorimeter. The effective geometrical factor of the apparatus is not less than $8-16 \text{ m}^2\text{sr}$ depending on the type of particles. Under the long exposure (~ 10 years), this mission will make it possible to precisely measure cosmic rays up to 10^{17}eV . Wide Monte-Carlo simulations were performed to obtain instrument response for different species of cosmic rays, including charged particles and gammas.

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1. Introduction

The central task for understanding of the origin of cosmic rays, their acceleration and propagation in the Galaxy is an interpretation of energy spectrum steepening at 10^{15} - 10^{16} eV (the knee phenomenon). Indirect methods based on expanded atmospheric showers (EAS) registration depend on applied interaction models. It causes significant differences in physical interpretation of obtained data. There are different hypotheses explaining the phenomenon of the knee. Direct measurements of the energy spectra and the chemical composition of cosmic rays are necessary to solve this problem. It is necessary to determine secondary (generated by interaction with interstellar medium) to primary (generated in sources) nuclei ratio at >100 GeV/n for a study of mechanisms of the cosmic rays propagation in the Galaxy. The cosmic-ray anisotropy is a fundamental problem too. For example, the anisotropy can depend on stochastic character of supernova explosions. The very important problem is investigation of electrons energy spectrum at maximal energies. For high energy electrons the dominant energy loss mechanism is the synchrotron radiation when traversing through the galactic magnetic fields. Therefore, the propagation distance for ultrarelativistic electrons is limited. The high energy electrons spectrum depends on actual nearby sources of cosmic rays. High energy cosmic rays interact with the interstellar gas or the interstellar radiation field, and produce γ -rays via nucleon-nucleon interactions, electron Bremsstrahlung and inverse Compton scattering. Thus diffusive gamma rays are probe for cosmic rays distribution in the Galaxy. During last decade search of exotic phenomena is performed to determine characteristics of dark matter particles and to find strangelets. The annihilation or decay of hypothetical dark matter particles can cause fine structure in electrons and diffusive gamma energy spectra. Registration of cosmic ray nuclei with anomalous charge to mass ratio should be evidence of strangelets presence.

2. General requirements

Direct cosmic rays researches are performed for more than 60 years. During last decade “new generation” experiments based on precision techniques have been performed. Long-duration balloon experiments like ATIC [1], TRACER [2], CREAM [3] allowed to determine fine structure of cosmic rays spectra up to 10^{14} eV. With huge interest new data on protons, nuclei and electrons spectra obtained by space experiments PAMELA [4], AMS02 [5], ATIC [6], FermiLAT [7], NUCLEON [8], CALET [9], DAMPE [10] was accepted and interpreted. Above-mentioned experiments won't be able to solve completely these tasks. The main difficulty is insufficient exposition factor for cosmic ray registration for energy range 10^{11} - 10^{16} eV. The “final” large-scale experiment is necessary. This experiment must be based on application of last achievements of experimental techniques and space technologies.

The total cosmic rays intensity is presented in Table 1. For minimal statistics (100 particles at the end of range) exposition factor must be larger than $100 \text{ m}^2\text{sr year}$ for a large scale new experiment.

Table 1.

>E eV	10^{14}	10^{15}	10^{16}
N (m ² sr year)	2100	46	0.8

According to tasks the resolution requirements to the experimental device can be determined. The energy resolution must be better than 25% for nuclei to reconstruct energy spectra and 5% for electrons and gamma to detect possible spectral peculiarities. The charge resolution must be better than 0.2 charge unit for elemental separation including rare secondary nuclei. The rejection level for electron/proton separation must be better than 10^4 at 10^{11} - 10^{12} eV and better than 10^5 at 10^{12} - 10^{13} eV to separate electrons from proton background. The rejection level for gamma/electron separation must be better than 10^2 for all energy range.

Now the most universal energy measurements technique is ionisation calorimeter. According to simulation results the above-mentioned parameters can be achieved with thickness larger than 25 radiation lengths and 5 hadronic interaction lengths. The wide aperture ($\sim 2\pi$) is necessary to increase geometrical factor. The calorimeter must be homogeneous to register tracks with different directions. The detail cascade registration is necessary for electron/hadrons selection. The additional rejection can be achieved by means of registration of neutrons. Charge measurements can be performed by silicon detectors that were elaborated for accelerator and space experiments. Multi- layer segmented detector system can provide charge resolution and gamma rejection requirements.

The ionization calorimeter is a sufficiently reliable technique but this method is limited significantly by need of heavy absorber to be launched into the orbit. According to the physical conditions the weight of scientific device must be larger than 12 t. The long-time exposition of the device is necessary. During all exposition time angle orientation information must be registered. The reliable and continuous power supply and temperature regulation are necessary too. Thus technical characteristics of heavy space vehicles must be taken into account. Heavy class space vehicle designing is necessary. The vehicle characteristics must be close to long-term space station ones except for life support system. The angle orientation determination precision must be better than 1-3 minute. Power supply, temperature regulation, orbit correction system must function more than 10 years.

3. Experimental techniques optimization

The HERO calorimeter must consist of 15 identical layers. Every layer is a hexagon (25 mm thickness, 2025 mm circumscribed circle diameter). Ionization is registered by polystyrene scintillator (1 g/cm³ density). Absorber is made of tungsten-copper-nickel alloy (16 g/cm³ density). A layer consists of hexagonal scintillator cells (25 mm inscribed circle diameter). The absorber walls thickness is equal to 5 mm (~ 1 radiation length). This structure provide registration of electromagnetic and hadronic showers. The scintillator light signal is registered by the wavelength shifting fibers mounted in three angles ($X=0^\circ$, $Y=60^\circ$, $U=120^\circ$), Fig.1-3.

In each direction three fibers are laid in guides.

Each fiber group light signal is registered by one PMT. An opposite end face is polished and covered with a mirror covering. The calorimeter circumscribed circle diameter is equal to

2025 mm, height is equal to 455 mm. The mass is equal to 10 t. Number of information channels is equal to 3060.

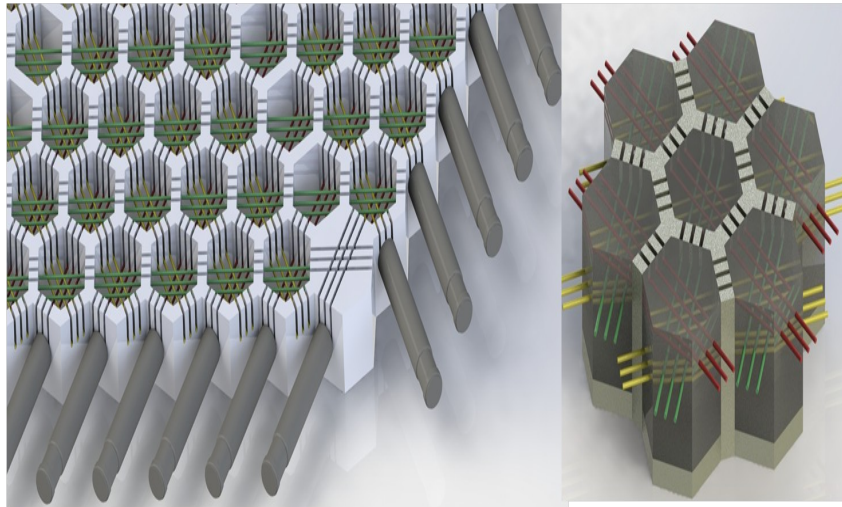


Figure 1: detectors layout .

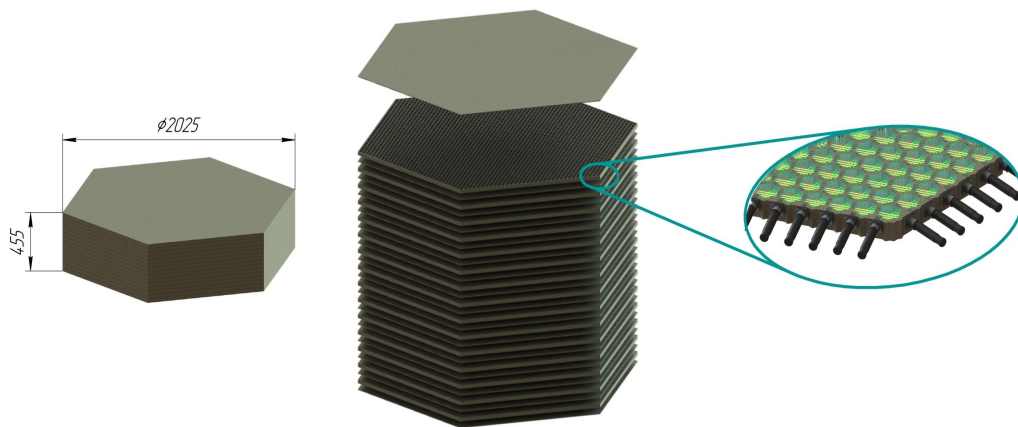


Figure 2: calorimeter

The calorimeter scheme is showed in Fig.4. The calorimeter is surrounded with silicon four-layer charge measurement system with overlapping not less than 95% of the area. Charge measurement system consists of independent ladders. Each ladder is mounted on planes and consists of 3-16 detectors (100x100x0.5 mm each one). Every detector is divided into 100 independent pads. There are ~ 2000 detectors in charge measurement system (i.e. $\sim 2 \times 10^5$ independent channels). The calorimeter and charge measurement system are placed inside the cylindrical vessel, truncated on the bottom side of a calorimeter, and established on a bearing platform. The scheme of charge measurement system and the vessel is presented in Fig.3

Additional improvement of rejection can be achieved by neutrons registration. Number of neutrons generated by electromagnetic shower is significantly less than for hadronic shower with the same energy. For example neutron yield distribution is presented in Fig.5 for electron and proton at $E=10^{11}$ eV. Fig.6. To optimize scientific apparatus neutrons can be registered by

the same detectors as ionization losses. Scintillator includes gadolinium ($\sim 0.3\%$). Ionization and neutron signals are distinguished by time delay. Most of neutrons are thermalized and captured by Gd or escaped from spectrometer for $200 \mu\text{s}$. Neutrons registration improves rejection level and additionally at high energies ($>10^{14}$ eV) neutrons can be used to determine primary energy.

The optimal orientation is by a lateral side to the Earth. For this variant geometrical factor is about 50% larger than for parallel orientation.

The Monte-Carlo s of charge measurements was performed to determine charge errors.

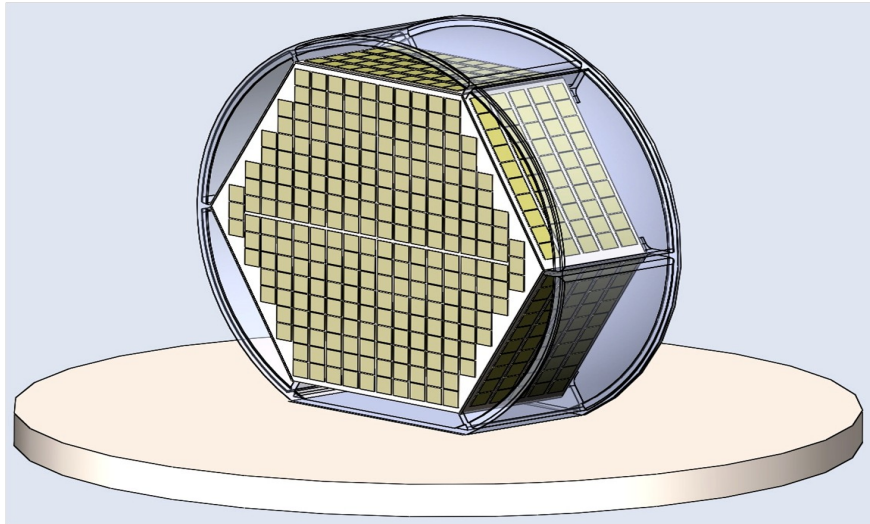


Figure 3: Schematical model of the instrument.

4. The HERO Monte-Carlo simulation

Wide Monte-Carlo simulations were performed to obtain instrument response for different species of cosmic rays, including charged particles and gammas. The goal of this work is to improve physical characteristics of the instrument to reach better the angular and energy resolutions than current space missions and ground-based experiments. GEANT Monte-Carlo model of the instrument is shown in figure 4. It is based on GEANT 4.10.03 patch01 simulation package (released 24 February 2017) with hadron model : **QGSP_BERT_HP**. HP (high precision neutron) model for neutron elastic, inelastic, capture and fission below 20 MeV, allow precise transportation of neutrons. Examples of simulated events are shown in figures 5-6. Along with the instrument simulation particles tracing in magnetosphere were performed to obtain detector response at different orbit positions and orientations. Figure 7 shows positron track in magnetosphere and figure 8 demonstrates detector angular distributions of electrons and positrons. Due to large instrument acceptance the method can be used for particle identification up to 100 GeV.

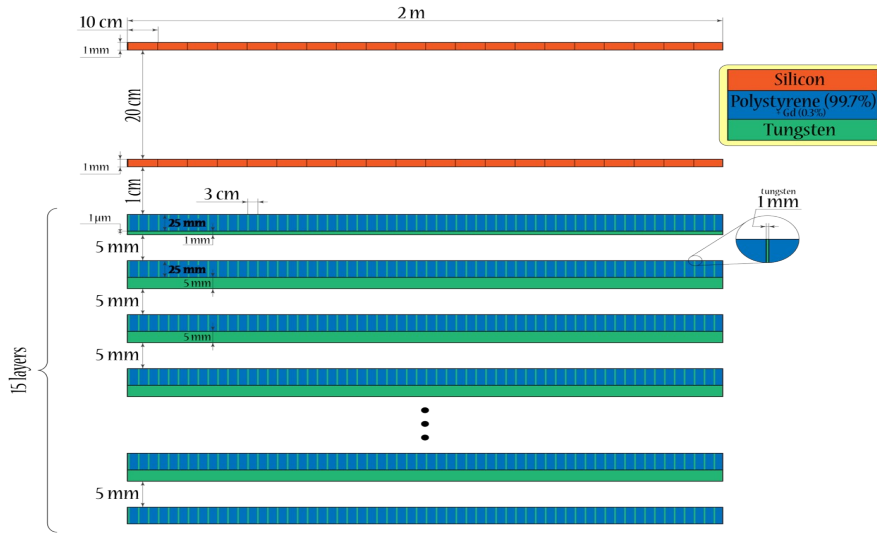


Figure 4: Monte-Carlo model of the instrument.

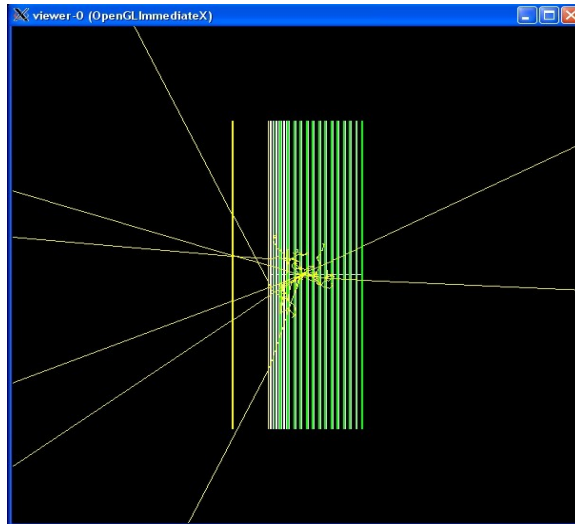


Figure 5: Simulation of neutron tracks from a proton interaction

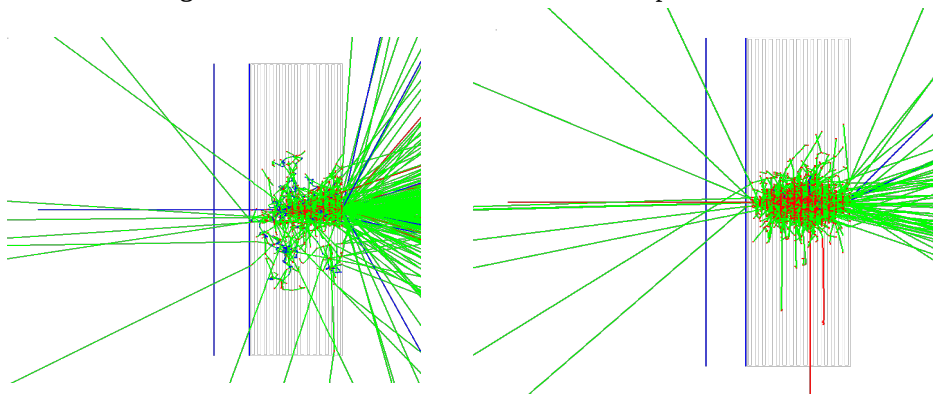


Figure 6: Examples of proton and electron events

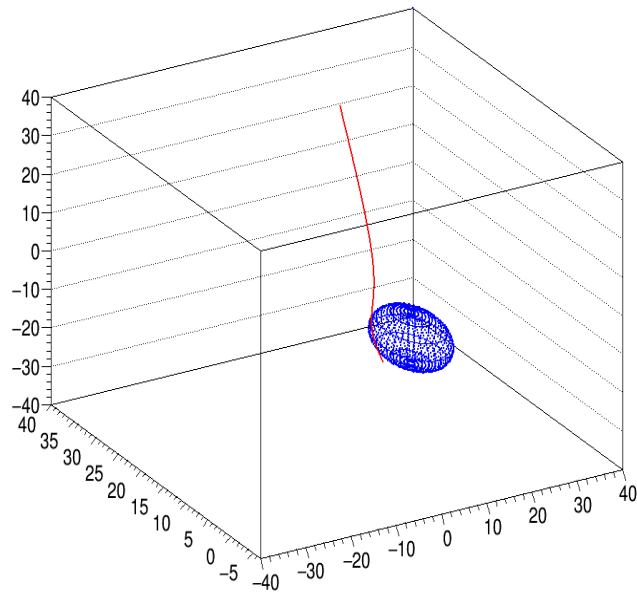


Figure 7: Simulation of positron trajectory in the Earth magnetosphere (IGRF-12 model is used)

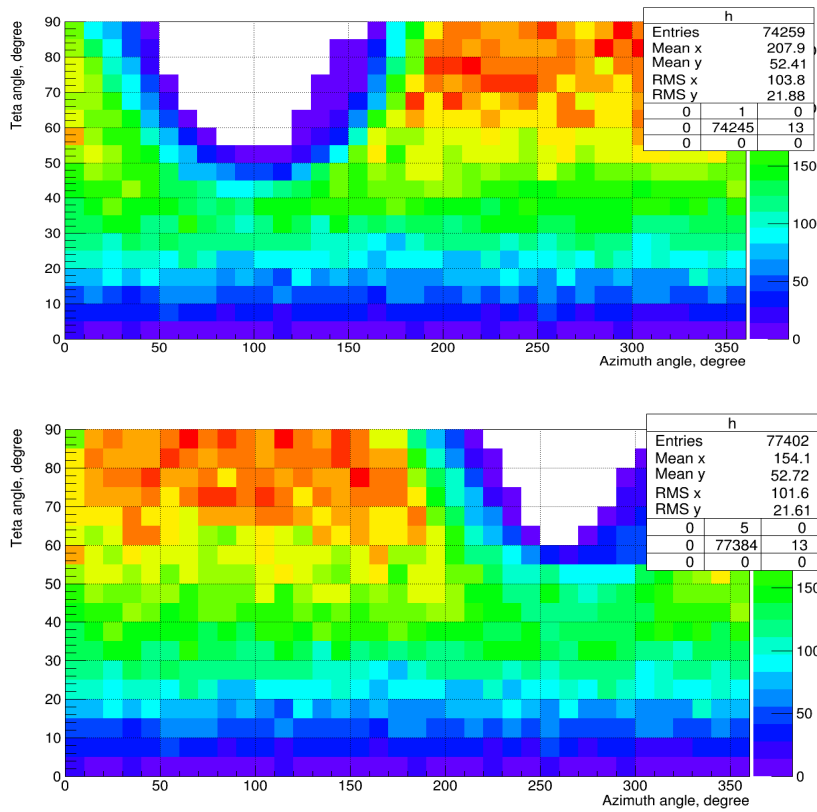


Figure 8: Simulated angular distribution of electrons (up) and positrons (down) with energy 20 GeV in the instrument reference frame

5. Expected characteristic of the HERO

Effective geometrical factor: protons 9 m²sr; heavy nuclei 14 m²sr; electrons and gamma 16 m²sr.

Exposition factor (10 years flight): protons 90 m²sr year; heavy nuclei 140 m²sr year; electrons and gamma 160 m²sr year.

Energy resolution: protons 25%, nuclei ~10-15%, electrons and gamma ~5%.

Charge resolution: 0.2 charge unit.

Rejection level: protons/electrons 10⁵-10⁶, gamma/electrons >10³.

Total mass 12 ton.

Power consumption <3500 W.

Overall dimensions: In transport situation the circumference is less than 2.5 m and the height is also less than 2.5 m.

6. Summary

Summary The HERO project is presented. The equipment is intended for the solution of the most actual problems of high energy cosmic ray physics. The combination of the last achievements of physical experimental techniques and modern level of development of the space industry allows to create unique space complex which could carry out the break data in the space science.

7. Acknowledgments

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