PROCEEDINGS OF SCIENCE

Detection of Extensive Air Showers with small array – measurement and estimations

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One of main objectives of Cosmic Ray Extremely Distributed Observatory (CREDO) is the search for Cosmic Ray Ensembles (CRE) - occurrences of correlated Extensive Air Showers (EAS). In order to confirm the existence of such phenomena large scale measurements of EAS signals and an analysis of their correlations in time are necessary. To make such observations possible, infrastructure of low-cost detector devices spread over the Earth and connected in a global network should be developed. The individual detector system registering an EAS should at least be able to give information about the time of detection. Such basic measurement can be performed by a few small scintillator detectors connected in a coincidence circuit. This study focuses on measurement using an array of very small detectors (area of 5 $cm \times 5$ cm each), which is currently being assembled. To determine if coincidence signals in such type of array can be a sign of an EAS event, a simulation-based analysis was conducted. Results from it are consistent with expectation that coincidence events caused by air showers have frequency orders of magnitude higher than those caused by all background sources, including uncorrelated single particles originating from low energy Cosmic Rays (CR). The analysis is based on multi-dimensional analytical parameterization of cosmic–ray showers derived from CORSIKA simulation results. Using such analysis it is possible to test expected efficiency of various detector systems and consider different models of cosmic ray spectrum composition without repeating time-consuming simulations. Presented work includes details of detector setup, simulation based predictions and planned measurements.

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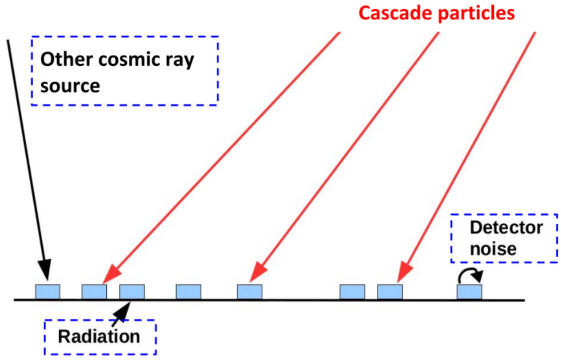


Figure 1: Sources of signals registered by an array of flat detectors.

1. Introduction

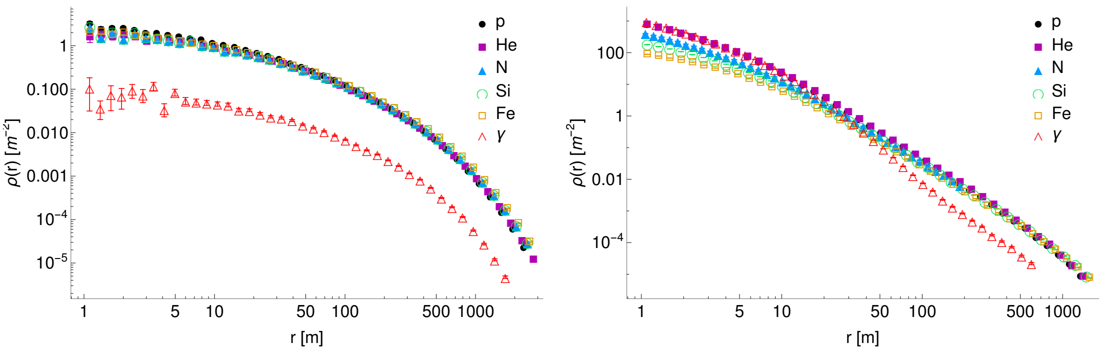
The main motivation for this work is to serve Cosmic Ray Extremely Distributed Observatory (CREDO) [1] which goal is to search for all sorts of global correlations and anomalies in cosmic rays (CR) data. Several scenarios of possible correlations are considered, like bursts of Extensive Air Showers (EAS) or groups of them correlated in time called Cosmic–Rays Ensembles (CRE) [2–4]. Most recently considered phenomenon that is exciting to study are correlations between the intensity of CR and seismic activity [5]. To study such kind of phenomena a global network of detectors should be developed. Currently, the main source of CR data for CREDO are smartphones which use custom designed application which turns their CCD cameras into particle detectors [6]. Main advantage of such solution is that it is almost free. This work proposes more advanced but still a simple and cheap detector station as a basic cell of such network. It also aims to provide tools for interpretation of data collected by such arrays. Proposed design is based on several scintillator detectors connected in a coincidence system. Signals in several elements in a very narrow time window indicate an occurrence of an EAS. It is however necessary to account for possible signals from other sources as illustrated in Fig. 1. The study presented in this paper aims to give answer how reliable and efficient such very simple systems can be. It also provides information that is necessary for proper data analysis and helpful in the process of improving the design.

2. Estimations

This section focuses on the analysis of simulations of EAS and their results in the form of expected frequency of given types of events.

2.1 Simulations

The samples of simulated EASes were obtained using CORSIKA software [7]. For simple recreation of composition of CR spectrum, data used in this analysis consist of simulations of 6 different types of primary particles: p, He, N (representing CNO group with Z from 3 to 9), Si (representing nuclei with Z from 10 to 22), Fe (representing the heaviest nuclei) and γ photons.



(a) $\rho_{norm}(r)$ for muons with $\epsilon \geq 1.0$ GeV. **(b)** $\rho_{norm}(r)$ for electrons with $\epsilon \geq 0.3$ GeV.

Figure 2: Density profile $\rho_{norm}(r)$ of muons (a) and electrons (b) for vertical cascades for different primaries at energy $E = 4000$ TeV. Density profile of photons is very similar to that of electrons shown in 2b.

For each primary particle 18 subsets of showers with different energies were simulated, from 1 TeV to 4000 TeV. These data sets contain from 300 showers for the largest energy up to 60000 showers for the lowest energy. For each energy, the same number of cascades with zenith angles varying from 0° to 70° with 10° step, were simulated. All showers were simulated at the sea level.

2.2 Analysis

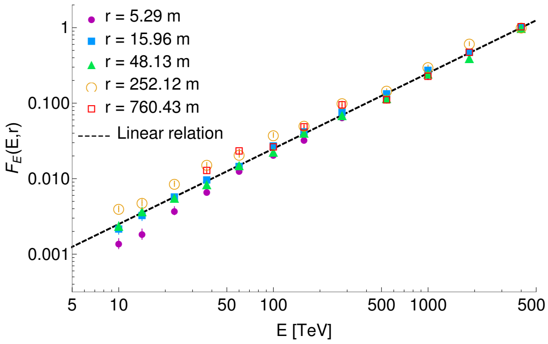
The goal of presented analysis is to provide tools to estimate expected frequency of coincidence signals in an array of several flat detectors. Let's start with definition of probability of detection of at least one particle from an EAS. From Poisson distribution it can be calculated as:

$$P(\eta, A, \rho) = 1 - \exp\left(-\eta \cdot A \cdot \rho\right), \tag{1}$$

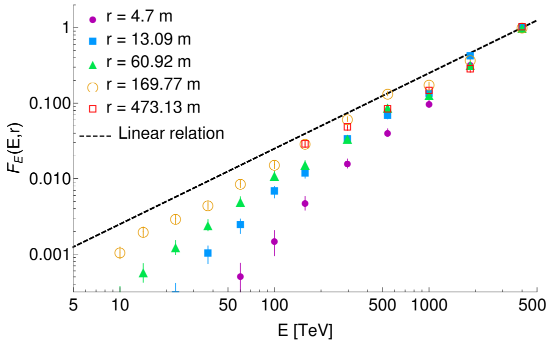
where ρ is the local particle density from the shower, A is the area of detector surface and η represents its efficiency. As A is known and η can be determined experimentally the only variable that needs to be derived is ρ. To do it, an analysis of simulations was performed in order to characterise particle density of cascades as a function of several parameters. The most important of them is the distance from shower axis, r, in the plane perpendicular to it. As vertical cascades are circularly symmetrical, this is a very reasonable choice. Other parameters that have significant impact on the produced particle density on the ground are the energy of primary CR, E, the number of produced particles, N, reaching the ground and the zenith angle of the cascade, θ. Final density is factorized as:

$$\rho(r, E, N, \theta) = \rho_{norm}(r) \cdot F_E(E, r) \cdot \frac{N}{N_{avr}(E)} \cdot F_N\left(\frac{N}{N_{avr}(E)}, r\right) \cdot N_\theta(\theta, E) \cdot F_\theta(\theta, r), \tag{2}$$

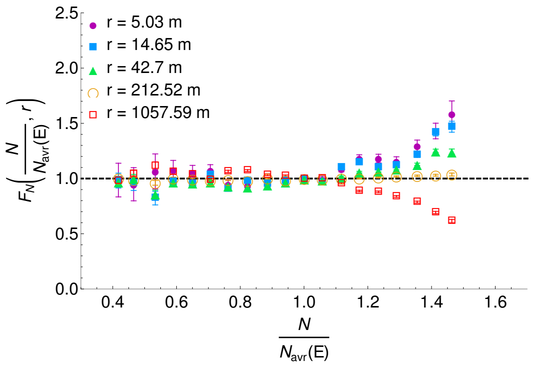
where ρ_{norm} is an average radial density profile for vertical cascade of given energy, $F_E(E, r)$ is a factor that modifies this profile with changing E, $N_{avr}(E)$ is an average number of produced particles for given E, $F_N\left(\frac{N}{N_{avr}(E)}, r\right)$ is a factor that modifies the linear density scaling with fluctuations of N, $N_\theta(\theta, E)$ is an average number of produced particles for given θ and finally $F_\theta(\theta, r)$ is a factor that modifies density profile with changing θ. Particles in the cascades are divided into three components: muons, $\mu^\pm$, electrons and positrons, $e^\pm$, and photons, γ. In the



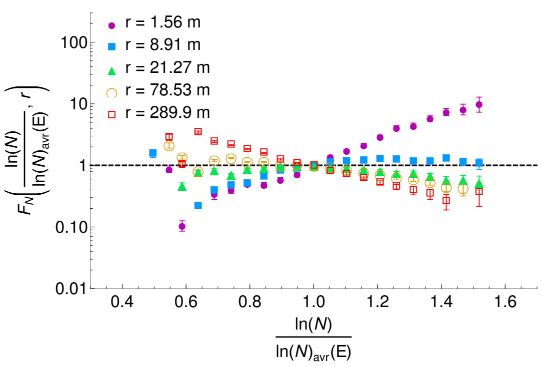
(a) $F_E(E,r)$ for p as the primary cosmic-ray particle and μ component with $\epsilon \geq 1.0$ GeV.



(b) $F_E(E,r)$ for p as the primary cosmic-ray particle and $e^{\pm}$ component with $\epsilon \geq 0.3$ GeV.



(c) $F_N(N,r)$ for p with $E = 100$ TeV as the primary cosmic-ray particle and μ component with $\epsilon \geq 1.0$ GeV.



(d) $F_N(N,r)$ for p with $E = 100$ TeV as the primary cosmic-ray particle and $e^{\pm}$ component with $\epsilon \geq 0.3$ GeV.

Figure 3: In Fig. 3a and 3b examples of $F_E(E,r)$ are presented. Fig. 3c and 3d present exemplary factors $F_N(N,r)$.

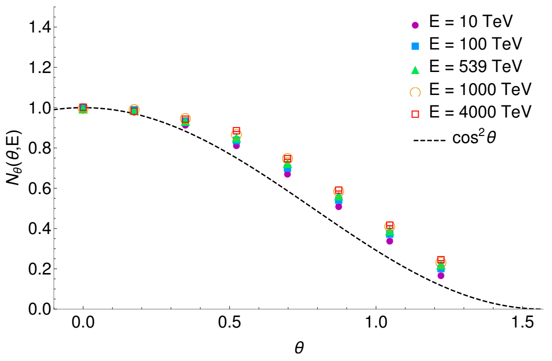
analysis only secondary particles with energy above a selected threshold, ϵ, are taken into account. Examples of $\rho_{norm}(r)$ factors for different components and primary particles are presented in Fig. 2. Factors $F_E(E,r)$ and $F_N(N,r)$ are presented in Fig. 3. Factors $N(\theta,E)$ and $F_\theta(\theta,r)$ are presented in Fig. 4. All factors in Eq. 2 are fitted to simulation data separately for each considered primary particle type, component of the shower and energy threshold considered.

2.3 Calculations

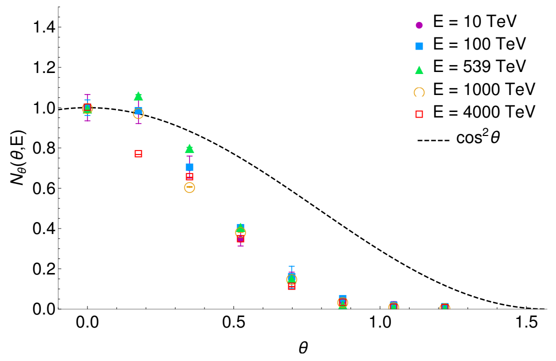
In this work it is assumed that the particle density from an EAS is the same for all detectors, which is reasonable for considered station of no more than ten pocket–size devices placed close to each other. Frequency of k-fold signals in array of K devices can be calculated as:

$$f_K(k) = \int_{E_{min}}^{E_{max}} \int_0^{2\pi} \int_{N_{min}}^{N_{max}} \int_0^{r_{max}} Q\left(K,k,P\right) 2\pi r\ j\left(E\right)\ dr\ dN\ d\Omega\ dE, \tag{3}$$

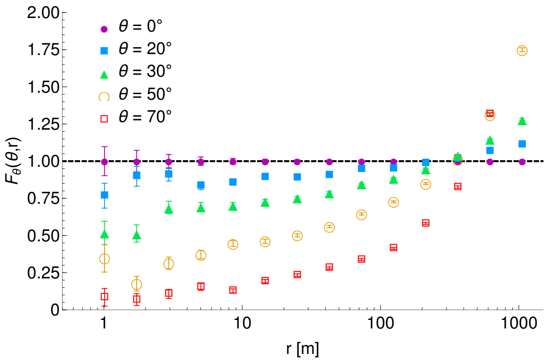
where probability $Q(K,k,P)$ is given by the binomial distribution . The limits of integration over E were chosen as $E_{min} = 1$ TeV and $E_{max} = 10^7$ TeV. Function $j(E) = j_0 E^{-\delta}$ represents a differential energy spectrum of given group of primary cosmic-ray particles with $\delta = 2.648$ for energies below E_{knee} and $\delta = 3.374$ above it. Values of j_0 for each primary cosmic-ray particle



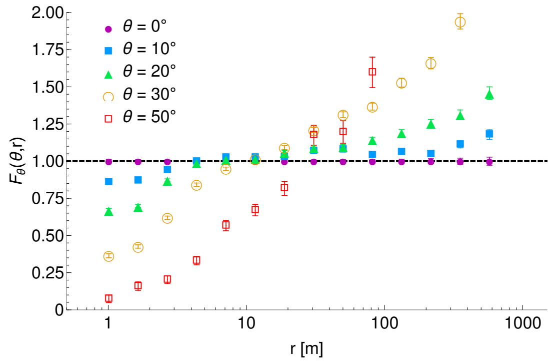
(a) $N_\theta(\theta, E)$ for p as the primary cosmic-ray particle and μ component with $\epsilon \geq 1.0$ GeV.



(b) $N_\theta(\theta, E)$ for p as the primary cosmic-ray particle and $e^{\pm}$ component with $\epsilon \geq 0.3$ GeV.



(c) $F_\theta(\theta, r)$ for p with $E = 1000$ TeV as the primary cosmic-ray particle and μ component with $\epsilon \geq 1.0$ GeV.

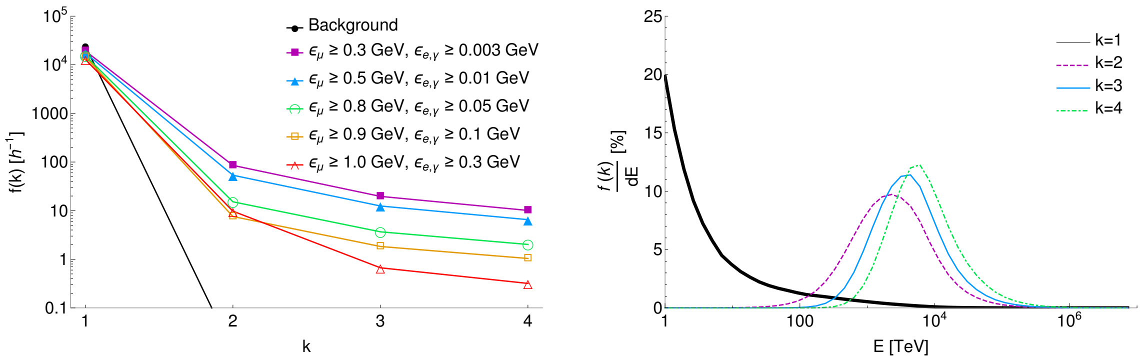


(d) $F_\theta(\theta, r)$ for p with $E = 1000$ TeV as the primary cosmic-ray particle and $e^{\pm}$ component with $\epsilon \geq 0.3$ GeV.

Figure 4: In Fig. 4a and 4b examples of $N_\theta(\theta, E)$ are presented. Fig. 4c and 4d present exemplary factor $F_\theta(\theta, r)$.

are chosen according to [8] and values of E_{knee} are chosen to match the summary function $j(E)$ from [9], from 6500 TeV for protons growing up to 185 000 TeV for iron nuclei. Distribution of the number of particles produced in the shower is normal for muons and log-normal for electromagnetic components. Thus, fluctuations of N are integrated over 3 σ range of those distributions. Integration over spherical angle Ω covers the whole sky. Distance limit, r_{max}, is a radius within which 95% of particles from the shower are located and is determined from simulations as a function of E. Evaluation of $f_n(k)$ is performed separately for each component and energy threshold.

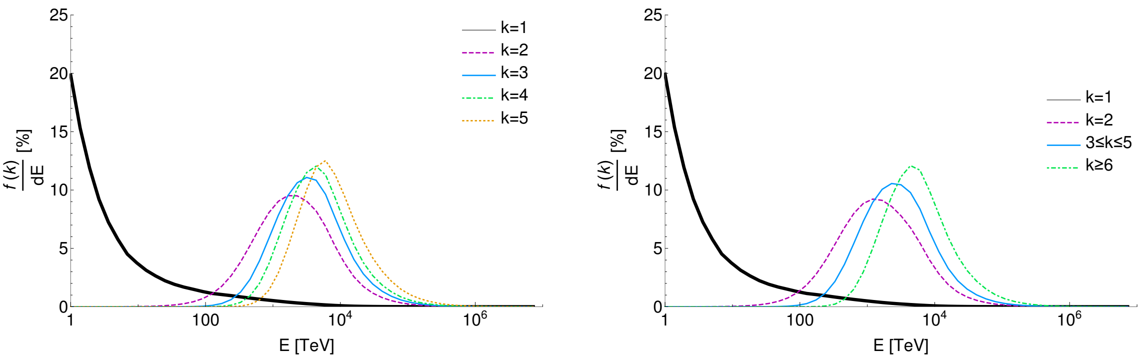
Estimation of results of measurements for detector array of four, $K = 4$, scintillator detectors with $A = 25$ cm^2 and $\eta = 95$ % are presented as an example. In Fig. 5a one can see that the expected frequency of multiple coincidence events which distinguish EAS from the background can be high, but it is very sensitive to energy threshold above which particles can be detected. Rate of signals caused by EAS can span over two orders of magnitude, from just a few to even 100 events per hour. What is interesting, increasing energy threshold for particle detection can sometimes cause 3 and 4–fold coincidence to turn into 2–fold events, increasing the rate of the last. Thus, determination of this threshold is crucial and should be performed either experimentally or analytically for each used type of devices, for proper data interpretation. From Fig. 6 a conclusion can be made that using



(a) Frequency of coincidence signals for different energy thresholds. Estimated background is a sum of fake electrical signals in the devices, $f_{bg} = 0.2\ Hz$, and uncorrelated CR with fluxes $I_{bg} = 70, 30$ and 51 $[s^{-1}m^{-2}sr^{-1}]$ for μ, $e^\pm$ and γ respectively [10].

(b) Percentage of signals caused by cascades of different energies for $\epsilon_\mu \geq 1.0$ GeV, $\epsilon_e \geq 0.03$ GeV and $\epsilon_\gamma \geq 0.03$ GeV.

Figure 5: Results of estimations for system of four detectors with $A = 25$ cm^2 and $\eta = 95\%$.



(a) Array of $K = 5$ detectors.

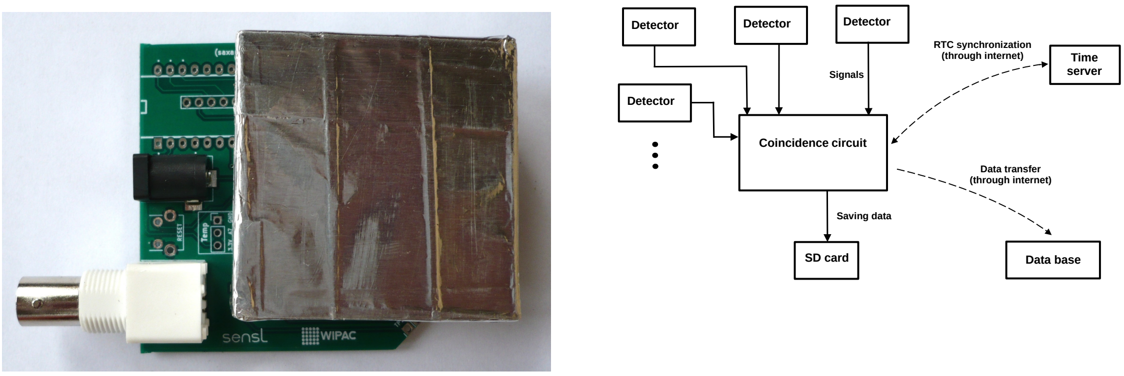
(b) Array of $K = 10$ detectors.

Figure 6: Percentage of different types of events caused by cascades of different energies for smaller 6a and larger array 6b. Calculated for $\epsilon_\mu \geq 1.0$ GeV, $\epsilon_e \geq 0.03$ GeV and $\epsilon_\gamma \geq 0.03$ GeV.

the number of signals in coincidence the minimal energy of primary cosmic-ray particle can be roughly estimated. Arrays containing more detectors should performed slightly better in this task.

3. Detector array

Proposed small shower array has a very simple design but it is able to both monitor the rate of cosmic rays signals and register occurrences of EAS. At the same time it allows to minimize the costs of such station. It consists of several small scintillator detectors based on Cosmic Watch [11] that are connected in a flat coincidence circuit. Similar designs has been tested in the past [12, 13], but this project focuses on making the simplest and at the same time most efficient arrays that could be produced in large quantity and operate without external support for a long period of time. The costs of constructing such station should be around $1000.



(a) **(b)**

Figure 7: Scintillator detector currently used for tests (7a). Diagram of proposed detector array (7b).

3.1 Scintillator detectors

The basic element of an array is a small plastic scintillator detector with active area of 5 cm $\times$ 5 cm. SiPM connected directly to the scintillator generates very weak analogue signal which is then amplified and transformed into logical signal. The signal is sent to the coincidence circuit through stereo audio connection which simultaneously is used to supply the device with power. One of detectors currently used for tests is presented in Fig. 7a.

3.2 Coincidence circuit

The coincidence circuit is a separate device with a processor (ARM Cortex-M7 600 Mhz) to which each scintillator detector is connected, as shown in the diagram of proposed station in Fig. 7b. It collects signals from detectors and serves as a power supply. In addition it is equipped with thermometer, barometer and internet connection. Checking of coincidence is performed by a fast logic circuit which sends logic expression to the processor. Time window in which signals are considered to be in coincidence can be adjusted from values as short as 20 ns. However, ultimately it should be set to around 200 ns as it is roughly the time between the first and last particle from the shower reaching the ground. Collected data is a list of events with time of registering signal, information which devices gave signal in the coincidence window, temperature and air pressure. Uncertainty of the time of observation of EAS would be equal to the sum of this time window, uncertainties of time delays in the electronic circuits and uncertainty of time readout from RTC. It will result in a time resolution of 1 ms or better, which is more than enough to study correlations between such events separated even only dozens of kilometers from each other. Metadata contains ID of the station and its location in the form of coordinates. Currently the data is saved in a SD card, but in the future a system sending data to the server will be developed.

4. Summary

Up to date analysis shows that small detector arrays should be a good tool to study not only cosmic ray flux in real time but also time correlations between individual EAS. Frequency of observed events should be high enough to provide good amount of data. Cost of proposed station is relatively low, thus creation of a network of such devices should be possible in a near future. Such network would be a good source of data about behavior of cosmic rays on larger scale. However before that, a lot of test measurements have to be conducted. Comparison of their results with analysis of simulations is necessary for proper data interpretation and final improvements in the design.

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