DESIGN OF THE EAS CHERENKOV ARRAY FOR THE CERRA LA NEGRA SITE

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The design of the air Cherenkov detector array for the Cerra La Negra site (an elevation of 4 km) is presented. The important features of the design are: the autonomous operation of the detectors, the low power-consuming electronics supplied by solar panels and batteries, and laser communication lines. The array combined with the water Cherenkov EAS particle detectors will provide the information on an EAS core position, the primary energy, the direction of the primary particles, temporal profiles of the EAS pulse in air Cherenkov and particle detectors. Studies on the EAS development above a shower maximum are among the main goals of the experiment.

1. Introduction. In studies of Extensive Air Showers (EAS) generated by high energy cosmic rays, the registration of the Cherenkov radiation produced by EAS charged particles moving faster than light in the atmosphere is one of the most informative methods. The flux of the Cherenkov photons coming to the observation plane is concentrated in a thin disc (several meters thick) with effective radius R_{eff} of about one hundred meters. The photon flux has axial symmetry and its density goes down with the distance from the shower axis due to the "Lateral Distribution Function" (LDF). Experimental data on the photon density and on the signal arrival time in several Cherenkov detectors separated by a distance $L \geqslant R_{\text{eff}}$ allow one to measure the direction of a primary particle and its energy (proportional to the total flux of the Cherenkov light). Statistics of the registered EAS depends on a sensitivity area Σ of the air Cherenkov array. The area Σ can be made larger if the Cherenkov array consists of standard modules repeated several times. The array triggering system and the data acquisition system demand communication lines between detectors in the modules, between the modules and the registration center. The whole Cherenkov array is a network of many detectors uniformly spread in area and operated by the registration center.

Some methodical problems arise in the realization of the air Cherenkov array:

— the array operation is restricted by sky noise at night; the existing arrays operate only during moonless nights (the duty cycle of 5 – 10 %);

— the air transparency at the array site should be controlled in order to perform accurate primary energy measurements.

Puebla University plans to construct the air Cherenkov array at the mountain level (the Cerra La Negra site, elevation 4 km). The design of the array presented below meets the above problems. The improvements of the design are based on the preliminary research done at Moscow State University [1]. In the design of the air Cherenkov detector (an open photomultiplier tube) capable to operate under intensive noise of light, the Russian-made tube FEU-110 (with a multialcali cathode) was chosen. The tube will operate with a low intrinsic gain (a low voltage supply) due to a high gain of the electronic preamplifier. The tube operation was proved to be stable (linear in response to the Cherenkov signals) in the presence of scattered moon light. The amplifier has a low noise level and is low energy consuming. The use of the low PMT voltage and of the low energy-consuming amplifier makes it possible to decrease the Cherenkov detector energy consumption.

The air transparency at the Cerra La Negra site is much higher than at sea level; therefore, the control of atmospheric conditions is not crucial.

In the joint work of Mexican and Russian groups, the operation of an air Cherenkov detector comprising three FEU-110 tubes was proved to be stable even at the Puebla city site [2]. The laying of novel laser optical communication lines between the registration center and detectors and the use of solar panels as an energy source of the array units open the way to transform each detector into an autonomous station and to ease the employment of detectors under mountain conditions.

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2. Instrumentation for the detector array. The array module comprises seven Air Cherenkov Detectors (ACD): six of them are placed in vertices of a hexagon and the seventh detector is at the center of it. A distance L between the ACDs should be chosen for the purposes of the experiment: in a range of $L = 100 - 750$ m.

Each ACD is a combination of three open photomultipliers of the FEU-110 type. The multialclali cathode of each tube is 7 cm in diameter, the quantum efficiency of the cathode is 0.18 at wavelength 420 nm, and the tube dynodes are of a venetian blind type. The average operating voltage of the tubes is of about 1000 V and the average intrinsic tube gain is $3 \cdot 10^4$. The maximum anode current at night, when the detectors are illuminated by the scattered moon light, is 0.1 mA. The divider resistance is 2 Mohm, so that the current through the divider resistors is five times larger than the maximum tube current. The energy consumption by the three tubes of each detector is less than 1.5 W.

A battery (12 V) connected to the solar panel feeds the high and low power supply circuits. The low voltage supplier transforms the battery voltage to a voltage of ± 5 V stabilized with an accuracy of 1.5 %. The high voltage supplier (of the DC–AC–DC type) converts the battery voltage to a voltage of 0.5 – 2 KV stabilized with an accuracy of 0.1 %.

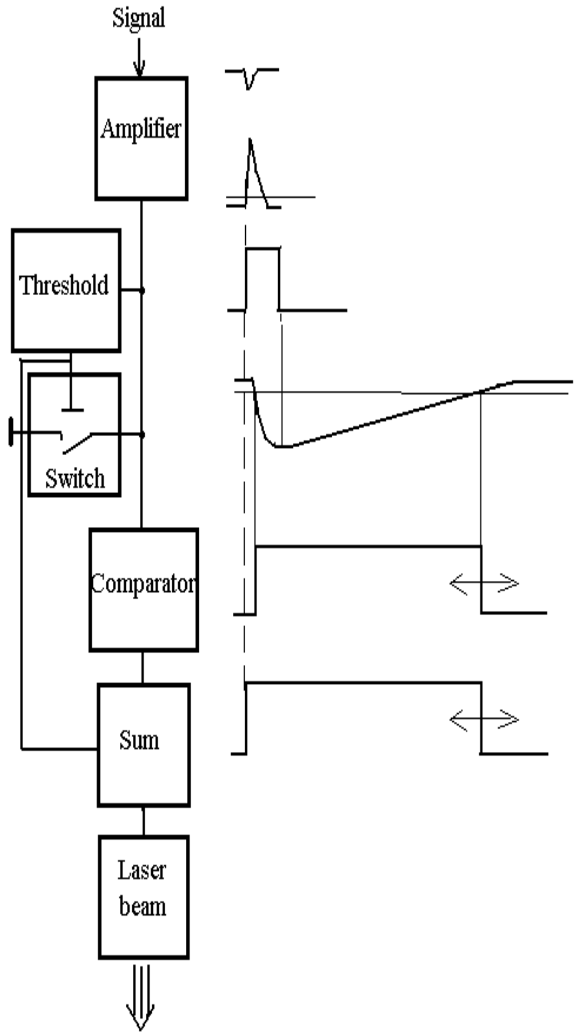

Fig. 1. The diagram of the ACD electronics operation

The operation of the ACD electronics is illustrated in Figure 1. Signals from each anode of the detector tubes go via attenuators to the preamplifier-summator. The gain of the preamplifier is of about 50, whereas each channel gain could be adjusted by the attenuator. Signals of the three tubes are equalized with the aid of the standard LED signal. The optimum preamplifier bandwidth for the Cherenkov signal (corresponding to an optimum signal-to-noise ratio) is achieved by adjustment of the amplifier RC. A signal from the amplifier goes to the discriminator (setting a signal threshold) that triggers the linear switch to an integrator. The integration time is chosen equal to the maximum expected Cherenkov signal duration (for the distance $L = 100$ m, the integration time is $\tau = 50$ ns, for $L = 750$ m it is $\tau = 300$ ns). In the integrator, the signal charges a capacitor, which later discharges linearly forming a triangular pulse at the integrator output. After amplification and inversion, the integrated signal comes to a comparator that forms a rectangular pulse with duration equal to the duration of the triangular pulse at a level of the signal threshold. The final rectangular pulse width is in proportion to the number of Cherenkov photons registered by the detector tubes. The signal from the last comparator is summed with a rectangular pulse of the first "threshold" discriminator, so that the arrival time of the summed signal becomes equal to the Cherenkov light disc arrival time. The width range of the summed signal (from 0.1 to 25 μs) covers the range of the number of Cherenkov photons registered in the detector (from 3 photons per cm^2 — the threshold signal during moonless nights — to $3 \cdot 10^3$ photons per cm^2). The summed signal comes to an E/O-converter (a laser diode), whereas the output optical signal is of the same rectangular shape. The time conversion to the optical signal is performed with an accuracy better than 10 ns. Optical signals from the air Cherenkov detector are continuously going to the registration center, where an O/E converter (a photomultiplier) is installed for each Cherenkov detector.

A test of the optical line transmitter has been done with the aid of a commercial laser pointer and a FEU-110 receiver at a distance of 200 m. The laser pointer emits more than 10^{12} photons during a minimum pulse width of 0.1 μs. The diameter of the beam at a distance of 200 m is 20 cm. The laser photon density on the receiver of the PMT is high enough for the optical line operation during a moonlight night.

In the detector electronics, there is also a control circuit of the tube current. A signal from the preamplifier goes to the current discriminator. When the tube current is higher than the threshold, the discriminator signal switches off the tube power supply.

The power consumption of the entire detector unit is less than 3 Wt.

3. A triggering system. Examples of the expected events. The array has to be triggered by three-fold coincidences of three detectors forming a triangle with a side L. A detector threshold is determined by a noise rate: the threshold is set to 4–5σ of the noise level during moonless nights (the expected night light intensity of 0.2 photons cm^{-2} ns^{-1} sr^{-1} yields $\sigma = 20$ p.e. for the integration time 100 ns). The voltage across the tubes has to be changed after moonrise, so that the rate of each detector will be constant — at a level of about 100 Hz. The resolution time of three-fold coincidences is chosen equal to 2 μs and a random coincidence rate is negligible in comparison with the EAS rate.

The module triggering is organized in the central detector (central station): each peripheral detector sends signals to the central station, where the coincidences are analyzed. The coincidence pulse triggers the digital oscilloscope trace, where all seven pulses from the module are recorded. A computer decodes the information on the arrival time and on the amplitude of each detector pulse. Then, the computer analyzes the EAS data to determine the EAS parameters: a core position and the primary particle energy and direction.

Since the air Cherenkov detectors are autonomous, it is easy to operate the array by changing the distance L between the detectors. We calculated the expected average EAS signals for several variants of the array geometry. The expected signals were calculated with the use of the experimental data on the Cherenkov light flux obtained with the Tjan Shan array [3] at an elevation of 3.6 km. These date were extrapolated to the Cerra La Negra site elevation and were approximated by the formula

$$Q_{\mathrm{Ch}}(r) = 3.0 \cdot 10^5 E^{1.04}/(0.3 + r/72)\,(1 + r/72)^{2.83+0.12\log E}$$

presenting the Cherenkov photon density (in photons per cm^2) in the EAS of energy E (E in EeV $= 10^{18}$ eV) at a core distance r (in m).

Some examples of the EASs "recorded" for various array geometries ($L = 200$ m, 500 m, 750 m) are shown in Figure 2, where the number of photoelectrons (p.e.) "recorded" at the tube cathodes for each detector is presented. For each array geometry, the primary energy is chosen so that at least three detectors were triggered at a threshold of 3 photons per cm^2. The corresponding EAS rates for these geometries and for these levels of energy are

L, m	200	500	750
E_{thr}, EeV	0.001	0.013	0.05
Rate, hr^{-1}	640	53	1.4

For the above energy thresholds, the accuracy in the core position is $0.05L$, the accuracy in the total Cherenkov light flux is 10 %, and the accuracy in the direction of a primary particle is $1°$–$2°$.

Fig. 2. The array module consisting of ACDs (triangles) and WCDs (circles). The separation L between the detectors takes the values: a) $L = 200$ m, b) $L = 500$ m, c) $L = 750$ m. The number of photoelectrons in ACDs and the number of particles in WCDs are indicated for the "recorded" EASs with the primary energy E: a) $E = 0.0011$ EeV, b) $E = 0.013$ EeV, c) $E = 0.05$ EeV

Changing the array geometry, it is possible to study different cosmic ray energy ranges, starting from a "knee" range of $0.001 - 0.01$ EeV.

The level of the EAS maximum is closer to Cerra La Negra than to sea level. This makes fluctuations of the Cherenkov light parameters (LDF, time width) larger. When $E > 0.1$ EeV, the position of a maximum for the proton initiated showers is, on the average, below the Cerra La Negra level, so that the proton initiated the EAS will be discriminated by the air Cherenkov trigger at this level. It is also expected [4] that if the energy is much above 0.003 EeV, then the heavy primaries prevail in the cosmic ray composition. Both the above factors make it very probable that the EAS of energy $E > 0.03$ EeV detected by the air Cherenkov array at the Cerra La Negra site will be mostly initiated by heavy nuclei. The goal of the experiment is to study the development of the EAS initiated by heavy primaries at the early stage of the cascade. It could be done by the study of Cherenkov LDF fluctuations and by the study of the temporal profiles of Cherenkov pulses. At core distances $R > 500$ m, the Cherenkov pulse is larger than 50 ns in width and the PMT of the FEU-110 type is fast enough for the observation of a real EAS profile. For distances $R < 500$ m, faster tubes should be used.

Along with the air Cherenkov detectors, the EAS particle detectors (the water Cherenkov detectors of the Auger array type [5, 6]) are planned to be installed at the Cerra La Negra site. The module of this installation is shown in Figure 2. At each air Cherenkov detector site, the water Cherenkov detectors of area 10 m^2 are placed. The signals in these detectors (in units of a "vertical equivalent muon", VEM, see [6]) are represented in Figure 2 along with the signals in the air Cherenkov detectors. These signals were calculated with the use of the Haverah Park LDF [7] as follows:

$$HP(E,R,\theta) = CE^b/R^{3.49-1.39\sec\theta+0.15\log(E/0.1)+R/4000} \quad \mathrm{VEM/m^2}$$

Here E is expressed in EeV, whereas the coefficients $C = 1.23 \cdot 10^7$ and $b = 1.4$ are given for an elevation of 4 km.

In the final version of the array, the water Cherenkov detectors will be concentrated at the array center with the separation $L = 200$ m between the detectors. An extended array of the air Cherenkov detectors with the separation $L = 750$ m will surround the compact central part. By this array, EAS of energies more than 0.1 EeV will be recorded with a rate of about 1 per hour with cores at an average distance of about 500 m from the central part. In the cluster of water Cherenkov detectors, the total signal will be high: more than 100 VEM. The time resolution of the water Cherenkov detectors (tens of ns) allows one to study the time structure of an EAS signal at distances $R \geqslant 500$ m, where the signal width is more than 140 ns [6]. Data on the time structure of signals in the air and water Cherenkov detectors will help one to analyze the EAS development above the mountain level.

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