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The FARCOS project: First characterization of detectors

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Summary. — The construction of a new array to study femtoscopy and multi-particle correlations in heavy-ion collisions at intermediate energies ($E = 20$–1000 A MeV) has been started at the INFN of Catania (Sezione and LNS). The project, named FARCOS (Femtoscope ARray for COrrelations and Spectroscopy) is aimed at the development of a detection system with high pixelation capabilities in order to perform high-precision measurements of two- and multi-particle correlations. The detector will address topics related to the study of reaction dynamics and of the equation of state of asymmetric nuclear matter as well as spectroscopy with both stable and exotic beams. We present first detection simulations for FARCOS telescopes and first experimental results related with the characterization of CsI(Tl) crystals, an important detection stage of each telescope.

PACS `29.40.Gx` – Tracking and position-sensitive detectors.
PACS `29.40.Mc` – Scintillation detectors.

1. – Introduction

Heavy-ion collisions allow one to explore the properties of nuclear matter under extreme conditions. These reactions give the opportunity to study the time scale in transport phenomena and to characterize the decay and break-up of unbound states with the relative branching ratios. In order to extract such nuclear matter properties, a clear understanding of the complex dynamics of heavy-ion collisions is required. Such challenge can be accomplished by using two- and multi-particle correlations. The correlations between different particles emitted during a collision provide important information about space-time properties of the emitting sources produced and quantitative understanding of reaction dynamics. Figure 1 shows two protons correlation functions in the case of $^{14}\mathrm{N} + {}^{197}\mathrm{Au}$ collisions at $E = 75\,\mathrm{A\,MeV}$ [1]. The peak at relative momentum $q = 20\,\mathrm{MeV}/c$ is due to the nuclear interaction between the two protons and determines the spatial extent of the emitting source, $S(r)$, defined as the probability of emitting two protons with a relative distance r recorded at the time when the second proton is emitted. The right panel of fig. 1 shows the source function, $S(r)$, extracted from the

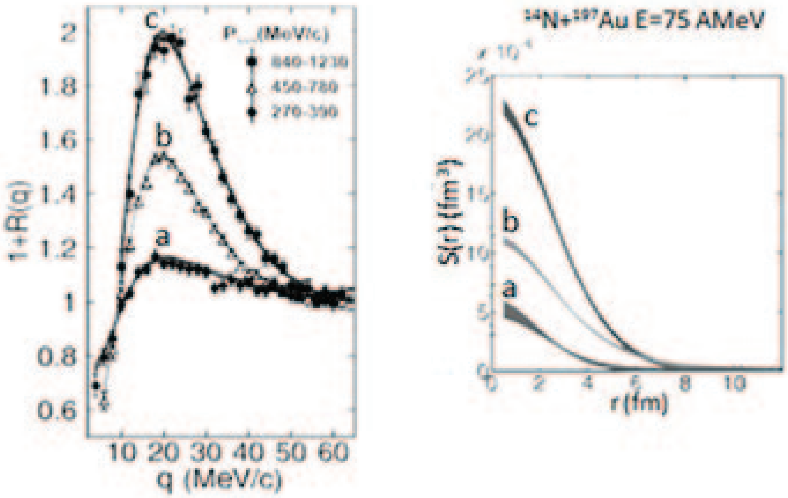

Fig. 1. – Left panel: Two-protons correlation functions measured in $^{14}\mathrm{N} + {}^{197}\mathrm{Au}$ collisions at $E = 75\,\mathrm{A\,MeV}$. Right panel: emitting source functions extracted by imaging technique [1].

correlations represented on the left panel. The source function not only provides information about the size/volume of the emitting source, but also allows us to estimate the relative contributions of fast dynamical pre-equilibrium sources and slowly evaporating sources characterizing the later thermalized stages of reactions.

The study of correlation functions can also be used as a powerful tool to explore certain spectroscopic properties of unbounded states of exotic nuclei, such as spin of excited states and branching ratio for the decay to specific channels [2]. During the dynamical evolution of a system several loosely bound nuclear species are produced for a very short time and subsequently decay. Their unstable states can be identified and explored by detecting all their decay products in coincidence. Figure 2 shows p-^{7}Be correlation function from which it is possible to extract important spectroscopic information of ^{8}B, as the spin of first excited levels. For all these studies, precise measurements of relative energies and angles are very important. In order to reconstruct the exact shape of correlation functions, specially at low values of relative momentum, high energy and angular resolutions are required. For these reason the FARCOS (Femtoscope ARray for COrrelations and Spectroscopy) project is aimed at the development of a detection system with high pixelation capabilities, to perform precision measurements of particle correlations for nuclear dynamics and spectroscopy. FARCOS has been conceived as a compact high resolution array; the basic telescope consists of two double-sided silicon strip detectors (DSSSD) $300\,\mu$m thick and $1500\,\mu$m thick, as first and second stage, respectively, followed by 4 CsI(Tl) crystals arranged in square configuration 2×2, as a third stage. The total detection area of silicon detectors is $64 \times 64\,\mathrm{mm}^2$, adapted to cover the total area of the four CsI(Tl) crystals placed behind. The scheme of the different stages of one FARCOS cluster is shown in fig. 3.

Each DSSSD features 32 horizontal and 32 vertical strips providing 1024 equivalent pixels of $2 \times 2\,\mathrm{mm}^2$. This segmentation allows to reconstruct with high accuracy the impact position of detected particles (hence their emission angles with high resolution)

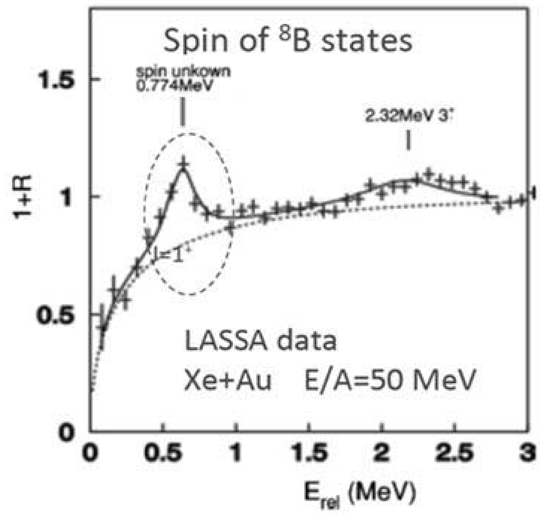

Fig. 2. – ^{7}Be-proton correlation function measured in Xe + Au collisions at $E = 50$ A MeV. See ref. [2] for details.

for events with multiplicity $M = 1$ for each telescope. In some cases ambiguities related to multiplicity greater than one could be solved if particles hit different CsI(Tl) crystals, or through pulse shape analysis on the signal coming from silicon detector. Anyway simulations performed for our studies shown that events with $M > 1$ on the same CsI(Tl) have a very low yield and are negligible. High angular resolution combined with high energy resolution provide a good measurement of relative energy, momentum vector and so their correlation. For FARCOS telescopes a wide dynamic range going from MeV to GeV is expected, therefore low thresholds will be attained with pulse shape techniques [3]. Silicon nTD solutions are also under consideration to improve pulse-shape capabilities, as

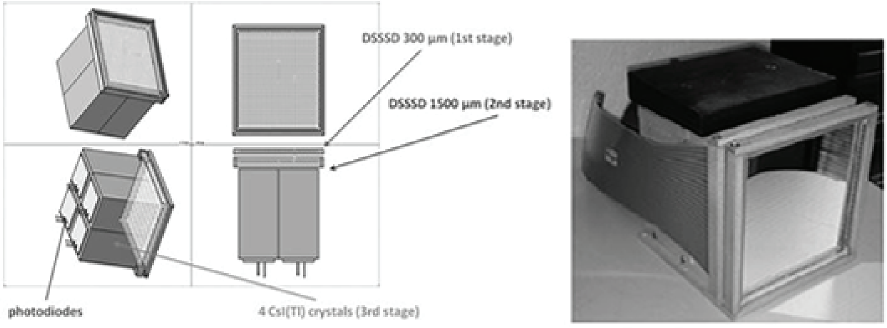

Fig. 3. – Left panel: schematic representation of a FARCOS telescope seen from different perspectives. Right panel: photo of one of first prototypes of FARCOS telescope.

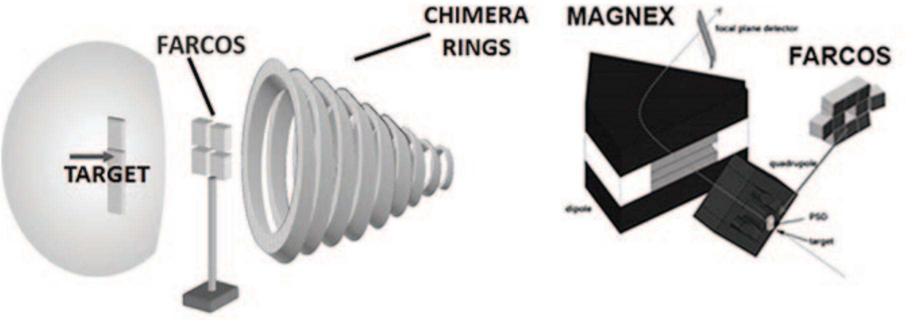

Fig. 4. – Left panel: possible coupling of FARCOS with CHIMERA. Right panel: possible coupling of FARCOS with MAGNEX.

observed in some experiments [4]. Furthermore, the flexible geometry allows to arrange FARCOS telescopes to cope with the physical case under investigation; it has been conceived as a portable device, so it can be coupled with other existing detectors. It will be interesting to use the FARCOS array in coincidence with large 4π array such as CHIMERA (see left panel of fig. 4) or INDRA, to have a good characterization of the collision events. Coupling to magnetic spectrometers (see right panel of fig. 4) and neutron detectors is also under study, to extend the physics reach of the project to spectroscopy studies conducted with stable and exotic beams.

2. – Simulation results

In order to understand the influence of angular resolution on reconstruction of physical observables of interest, hence on correlation functions, preliminary simulations were carried out.

It was chosen to simulate the decay of ^{6}Li in deuterium and alpha particle because this is one of the typical systems produced in heavy-ion collisions at intermediate energies. In this simulation it was assumed that ^{6}Li is evaporated, with a Maxwell distribution, by a source moving in laboratory reference system; a temperature of 7 MeV was chosen for the source. Simulated data were sent through a software that allow us to reproduce the effects of the detectors for all geometrical configuration of FARCOS array; this software takes into account all physical and geometrical features of the apparatus and it is also very useful in order to compare theoretical predictions with experimental observations. To show the effects of improvement of angular resolution, the results obtained with only one telescope and the ones obtained with 9 telescopes arranged in 3×3 configuration were compared. The two setup cover the same angular region but with different angular resolution, as evidenced by the plot in fig. 5: in the first case the average polar angle resolution is about $1.4°$, while in the second one is $0.5°$.

The scatter plots shown in fig. 6 report the ratio between the number of pairs detected by simulated configurations and the total number produced as a function of relative momentum Q_{rel}. For the second setup an enhancement of efficiency is observed. In the regions of interest of d-α correlation function, around resonances at 42 and 84 MeV/c, it is possible to obtain an improvement of efficiency by about a factor of 25 by using

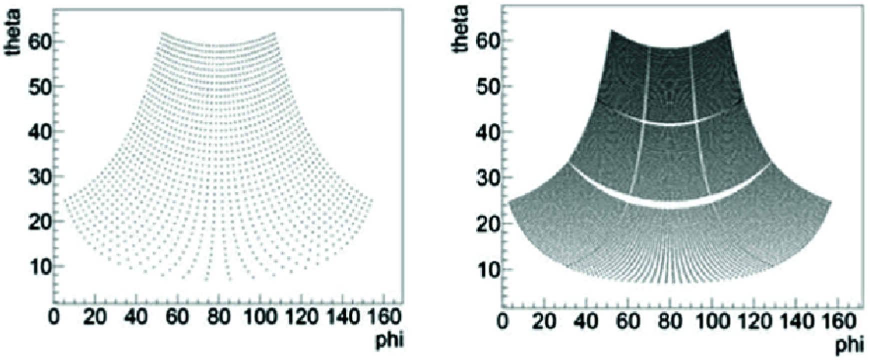

Fig. 5. – Angular resolution obtained with one (left panel) and nine (right panel) FARCOS telescopes covering the same angular region; the points in these plots represent the spherical coordinates of the center of the squares defined by the cross of front and back strips.

the setup with nine telescopes. A similar improvement is observed for relative energy reconstruction for particles stopped in the first two identification stage. The plots in fig. 7 report the deviation between the simulated relative energy (E_{th}) and the same observable (E_{fil}) filtered by chosen apparatus:

$$\delta E_{rel} = \frac{E_{fil} - E_{th}}{E_{th}}\,;$$

for small values of relative energy the error in reconstruction of the same observable increases: for the first setup these errors exceed 30% while for the second one they are of few percentage points. Figure 8 shows the δE_{rel} distributions for Q_{rel} values included between 82 and 86 MeV/c. In correspondence of resonances of d-α correlation function, in the second setup the energy resolution increases by a factor around 3 with respect to the first one.

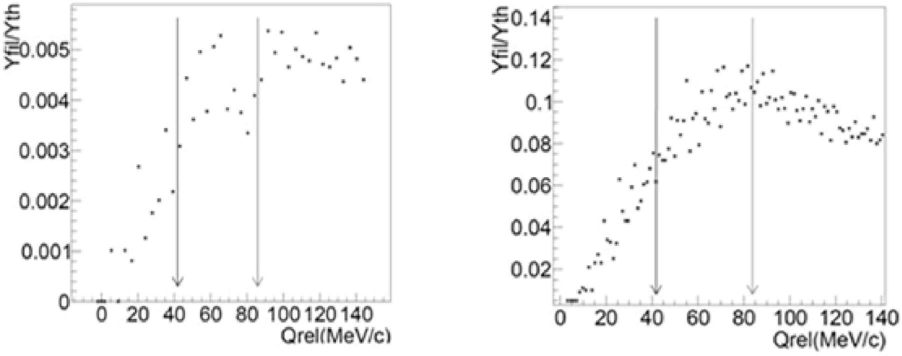

Fig. 6. – Scatter plots of ratio of number of detected particles pairs and number of produced pairs *vs.* the relative momentum Q_{rel} (left panel: one telescope; right panel: nine telescopes; see text for explanation).

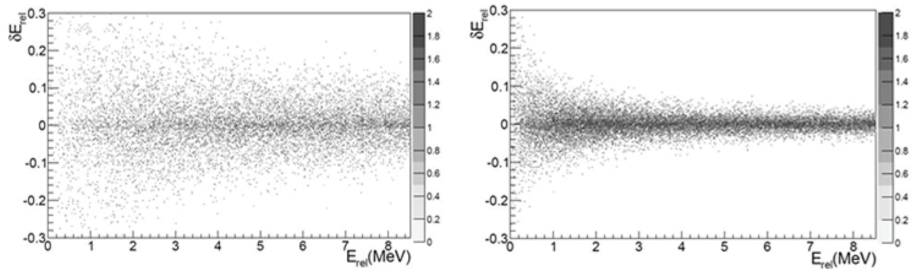

Fig. 7. – Deviation between the simulated relative energy (E_{th}) and same observable (E_{fil}) filtered by chosen apparatus: only one telescope (left panel) and nine telescopes (right panel).

So with a suitable setup it is possible to achieve the efficiency and resolution required for a proper reconstruction of correlation functions.

3. – Experimental results

A good reconstruction of the relative energy depends on both angular and energy resolution of the single telescope.

High-energy resolution is also required in spectroscopy applications in which it is important to separate very close energy states. For this reason several tests were conducted to estimate the resolution of each identification stage of FARCOS telescope. Concerning the tests made on the DSSSD, good resolutions have emerged, suited to our studies; with a mixed alpha source (about 5 MeV) the 300 μm silicon detectors show a resolution of about 45 KeV. The overall energy resolution of FARCOS telescopes depends mainly on the quality of the CsI(Tl) crystals. Several factors such as dopant concentration gradient, imperfections in crystal wrapping and/or in photodiode coupling can affect the energy resolution of CsI(Tl). In particular, the aspect that deserves special attention is a possible position dependence of light output of these crystals. For this reason, special tests have been carried out using firstly a collimated monochromatic alpha source, to scan the surface of the crystal and after, different particles beams to investigate a possible

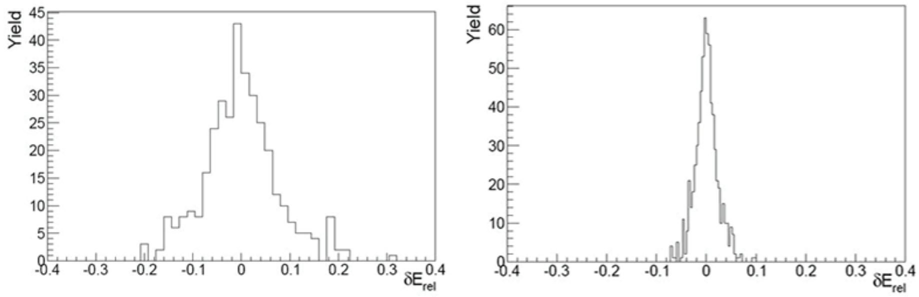

Fig. 8. – Left panel: δE_{rel} distributions for Q_{rel} values including 82 and 86 MeV/c as function of relative energy obtained using only one telescope. Left panel: δE_{rel} distributions for Q_{rel} values included 82 and 86 MeV/c as function of relative energy obtained using the setup with nine different telescopes.

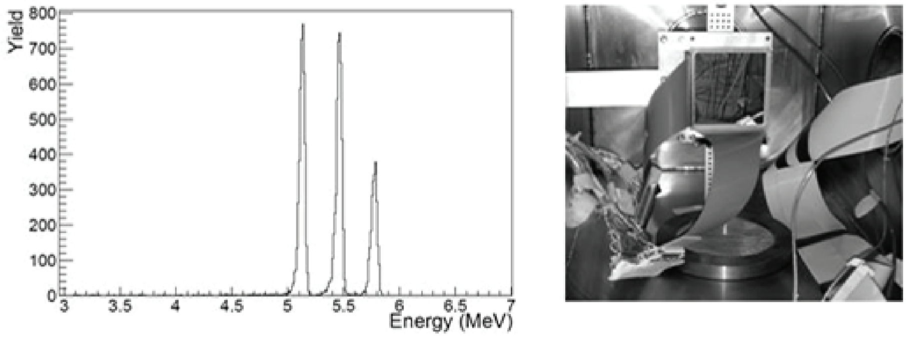

Fig. 9. – Calibrated α spectra for a 300 μm thick DSSSD and experimental setup for silicon detectors test.

non-uniformity in depth, searching for noticeable differences in the output signals. The dependence on the position of the CsI(Tl) crystals has been tested by means of an ^{241}Am α source. A special apparatus has been setup allowing to move the α-CsI(Tl) system in perpendicular directions inside the vacuum chamber.

The system was automatized in such a way that an energy spectrum was obtained for points separated by spacing of 2.7 mm on a 3 by 3 Cartesian grid on the front surface of the tested crystals. Using the information from the linear drivers used to move the source, discrete grids in the x-y coordinate plane are mapped on the crystal surface. At the coordinate $x = i$, $y = j$, the non-uniformity of light output is expressed as [5]

$$S_{ij} = \frac{L_{ij} - \langle L \rangle}{\langle L \rangle},$$

where L_{ij} represents the centroid of the energy peak at ij position, while $\langle L \rangle$ represents the average over the entire crystal.

Figure 10 shows the light response for two different crystals: in the left panel the non-uniformities exceed 4% while in the right one a very good uniformity (better than 1%)

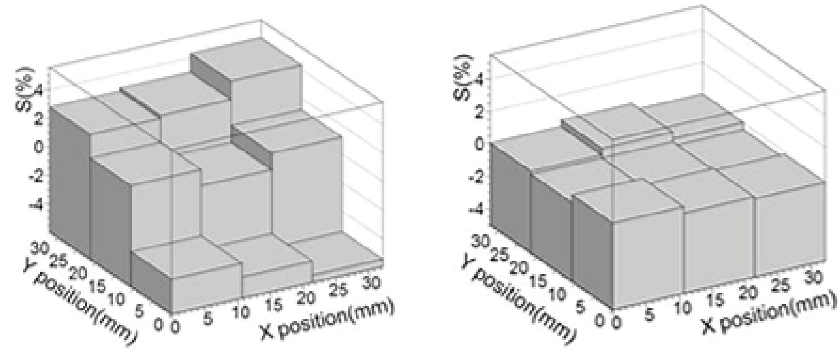

Fig. 10. – Characterization of light response of two tested CsI(Tl) crystals obtained with alpha source [6].

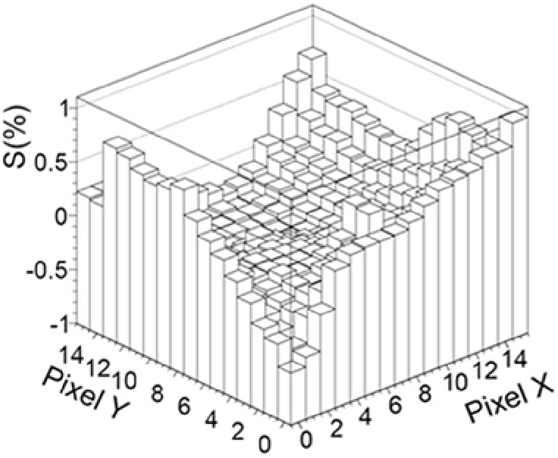

Fig. 11. – Characterization of light response for one of tested CsI(Tl) crystal using alpha beam at 62 A MeV scattered by ^{208}Pb.

is observed. Based on these relults, it is important to study the position dependence of light response with higher-energy α-particles. While α source tests involve a region of the crystal that extend up to only a few microns beyond the entrance window, measurements of light output performed with beam at higher energy allow one to explore the quality and uniformity in crystal response at different depths inside. To this aim an analysis was performed with data collected during a test made at LNS of Catania in the last months. In particular data relating to the reaction $\alpha + {}^{208}$Pb @ 62 A MeV were used. To search and identify any position dependence in the crystal light output, the position information is given by the DSSSD placed in front of the CsI(Tl) crystals. The strips provide tracking information by dividing the active area of silicon detectors into 1024 pixels, hence into 256 pixels for each crystal. Figure 11 reports light response of one tested crystal using 62 A MeV α beam, scattered by ^{208}Pb.

For all analyzed crystals the non-uniformity does not exceed 1%, then it is possible to distinguish energy variations of 2%.

These studies are important because the knowledge of the impact position (provided by the front DSSSD) allows one to correct for non-uniformities, largely improving energy

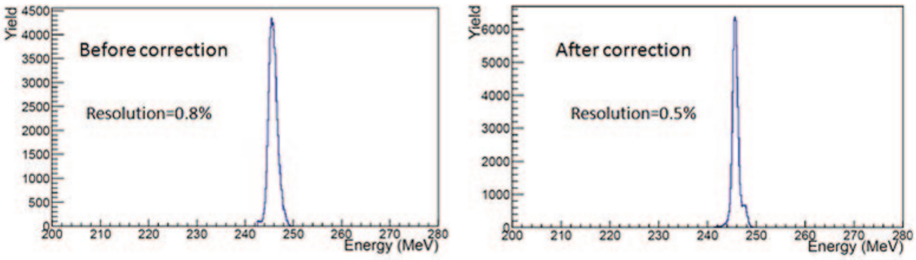

Fig. 12. – Total energy spectrum of one tested CsI(Tl) crystal before (left panel) and after correction (right panel).

resolution during the experiment. In fact one can correct energy light output pixel by pixel with the following correction factor:

$$K_{ij} = \frac{L_{ij}}{\langle L \rangle}\,.$$

Using K_{ij} for each pixel, an improvement of total energy resolution is obtained. As shown in fig. 12 energy resolution of CsI(Tl) (measured at $E = 62\,\mathrm{A\,MeV}$) can be improved from 0.8% to 0.5% after this correction.

4. – Conclusions and perspectives

The FARCOS apparatus, under construction at INFN of Catania and Laboratori Nazionali del Sud, will allow to study two- and multi-particle correlations with high energy and angular resolution for nuclear dynamics and spectroscopy. Preliminary simulations and tests were performed, in order to evaluate the energy and angular resolution achieved by FARCOS telescope. Silicon detectors analyzed show an energy resolution suitable for the study planned in the project. Possible non-uniformity in light respons of CsI(Tl) were estimated. By studying these non-uniformities in light response it is possible to apply corrections that can improve energy resolution of crystals. For this reason it is important to continue these studies for a deeper particle penetration into crystal by using high-energy beams. In parallel to these uniformity tests, a new front-end electronics optimized for the FARCOS requirement is being developed. Of course one of the main problems related to this array is the control and processing of signals produced by each channel (132 for each telescope). For the future, ASIC electronics with a digitalization system is being developed, in order to obtain more compact modules and a better processing of signal produced by individual channels.

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