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The Farcos project: Femtoscope Array for Correlations and Femtoscopy

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Abstract. The Farcos project (Femtoscope Array for Correlations and Spectroscopy) is discussed in this contribution. It consists of a new detector array designed and constructed by Exochim-Chimera group at INFN of Catania and Laboratori Nazionali del Sud. The array is described in its design and scientific goals to address. Some of the first preliminary tests with radioactive sources and beams are also discussed, together with some highlights of future perspectives.

1. Introduction

The study of particle-particle correlations provides powerful tools to extract information about the space-time properties of nuclear reactions. In particular, recent advances in analysis techniques based on imaging and inversion procedures have allowed one to extract the size (volume, density) of particle emitting sources produced during heavy-ion collisions, as well as their lifetimes [1]. These techniques have actually shown that high resolution in particle detection can provide much more details about the profile of the emitting source that can be used to compare to transport models of the reaction or to disentangle early pre-equilibrium emissions from late evaporative sources that follow thermalization of the system [2, 3]. In order to perform these measurements hodoscopes of silicon and scintillator crystals have become a typical detector array covering a reduced angular region in the reaction chamber. However the availability of

powerful 4π arrays [5, 4] have allowed extracting important information about the time-scale of fragment emission, significantly connected to the density dependence of the symmetry energy [6]. Furthermore, these arrays are a unique tool to characterize the whole collision event in terms of impact parameter, reaction plane, collective motion. These global features of the event play a key role in studying two-particle correlation functions [7]. Stimulated by these ideas the Farcos project as been designed to increase the already rich physics reach of the Chimera array to include studies of two- and multi-particle correlations in heavy-ion collisions at Fermi energies. The idea consists of having a relatively small array characterized by a high angular and energy resolution to be coupled to the 4π coverage of the Chimera system in different angular regions depending on the physics case to be addressed and on the beam energy and kinematics of the reaction.

In the next sections the project will be described from the point of view of the construction details and of the physics cases that are planned to be addressed by the combined setup Chimera+Farcos.

2. General description of the Farcos project

The FARCOS detector (Femtoscope ARray for COrrrelations and Spectroscopy) has been designed as a compact high resolution array. Each telescope of the array is composed by a sequence of double-sided silicon strip detectors (DSSSD) followed by CsI(Tl) crystals. The array will address topics covering both nuclear dynamics and spectroscopy with stable and radioactive beams. The main feature that allows such measurements is represented by the high angular resolution of the array ensured by the DSSSD detectors and their pixelation. Such resolution is mandatory in order to use imaging techniques, providing sort of "space-time" snapshots of particle and complex fragments emitting sources. Using these images allows probing fast and slow sources in heavy-ion collisions and the role played by the N/Z degree of freedom in nuclear reactions. This last topic has recently attracted the interest of the scientific community due to its links to the sub-saturation density dependence of symmetry energy [2, 3].

Besides the above mentioned dynamics topics, studying two- and multi-particle correlations allows one to identify the decay of unbound states in exotic fragments produced during the collision. The detailed study of these correlations, powered by high angular and energy resolution, is expected to isolate resonances and study important spectroscopic information such as their spin and branching ratios with respect to different prompt and sequential decay modes [8, 9]. While such studies would significantly profit from coupling Farcos to 4π detectors such as Chimera and Indra, the use of Farcos in experiments with magnetic spectrometers can also help in performing high resolution spectroscopy studies in reactions induced by exotic beams, including their implications in nuclear astrophysics topics related to the study of nuclei far from the valley of stability. Fig. 1 shows schematically a cartoon of how the history of a collision between heavy ions leads to the production of unbound states that can decay by multi-particle break-up. Among them we mention the case of ^{10}C decaying into $2\text{p}+2\alpha$ either simultaneously or through sequential paths involving intermediate states in ^8Be , ^{11}B or ^6Be and two- and three-body decays into different combinations of protons and alpha particles [9].

A recent work performed with the Chimera detector has shown possible indication of Boson-Condensate states in ^{12}C through the study of three-alpha decays [10]. The experiment consisted of the study of Ca+C collisions at 25 MeV/nucleon that are commonly used to explore reaction dynamics and projectile multifragmentation. The strong performances of Chimera over the whole solid angle allowed a complete reconstruction of ^{12}C quasi-projectile decays. These large coverage features can profit significantly from the coupling to arrays with high angular resolution. These results are indeed indicative of the fact that the Farcos project can extend the physics reach of heavy-ion collision studies if coupled to a high performance 4π detector like Chimera.

Similar studies can be also performed with high resolution experiments using radioactive

beams [11]. In this case the high resolution envisioned for Farcos is mandatory to the lower intensities of beams and to the requirements of reconstructing precisely the scattering angle by adding a precise determination of the impact position of the beam of the target spot.

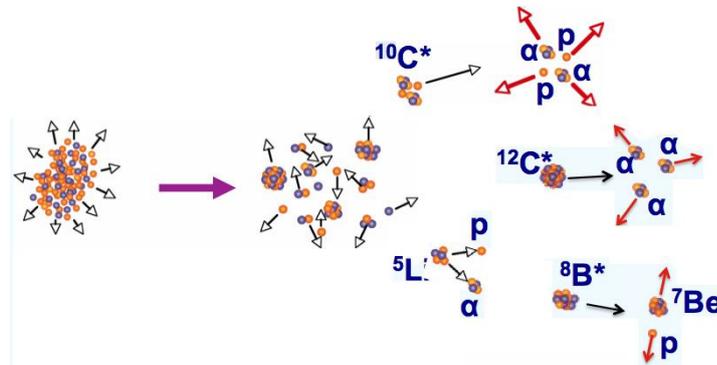


Figure 1. During a collision between heavy-ions the system expands and produces fragments that can be used to study the equation of state of nuclear matter. Some of the fragments can be produced in unbound states and decay multi-particle emission.

In order to accomplish the above mentioned goals, the design of Farcos has been established on the basis of the need for a high angular resolution, necessary to well define the direction of momentum vector of particles detected in coincidence. Farcos will be thus composed of telescopes forming clusters, where each cluster contains 4 CsI(Tl) crystals in a window shape of $6 \times 32 \times 32 \text{ mm}^3$, as a first stage, following two double-sided silicon-strip detectors (DSSSD) of 1500 and $300 \mu\text{m}$ of thickness, respectively, facing the target. The CsI(Tl) crystals are wrapped with a 0.12mm -thick white reflector and a $50\mu\text{m}$ aluminized Mylar. The front face of the crystal is covered with only a $2\mu\text{m}$ aluminized Mylar foil. The light produced by each crystal is read-out by photodiodes with a thickness of $300\mu\text{m}$ and an individual active area of $2.5 \times 2.5 \text{ cm}^2$.

Concerning the silicon strip detectors, each DSSSD is segmented in 32 horizontal and 32 vertical strips, from which it is possible to define 1024 individual pixels each covering an area of $2 \times 2 \text{ mm}^2$. The total detection area of each telescope is $64 \times 64 \text{ mm}^2$. A schematic drawing of the different stages of one FARCOS cluster is shown in Fig. 2, while Fig. 3 shows two pictures of a first telescope prototype with its very compact mechanical holding system designed by the INFN, Sezione di Catania.

Depending on the physics case one wants to address the Farcos array can be arranged in different configurations. Fig. 4 shows an example of two different types of mountings. The one displayed on the left side of the figure is expected to be used in cases when the decay of fragments produced by projectile excitation and breakup is studied. The array can be easily centered around the beam axis and placed inside a 4π detector in order to improve the event characterization. The configuration displayed on the right side of the figure is more suited to the study of two-particle correlations in heavy-ion collisions where a wall of high resolution telescopes is mandatory.

The signals produced in the silicon strip detectors are transported by means of flexible flat cables (see right panel on Fig. 2) and sent to pre-amplifier boxes mounted very close to the detectors. These hybrid charge sensitive pre-amplifiers have been designed by the INFN electronics group in Milano and are very compact, occupying a volume of only $8 \times 10 \times 2 \text{ cm}^3$ and housing 32 channels in one single package. The power consumption is less than 1W per all 32 channels powered together and can therefore be used inside the reaction chamber, under vacuum and as close as possible to the telescopes. Tests performed with pulser signals have

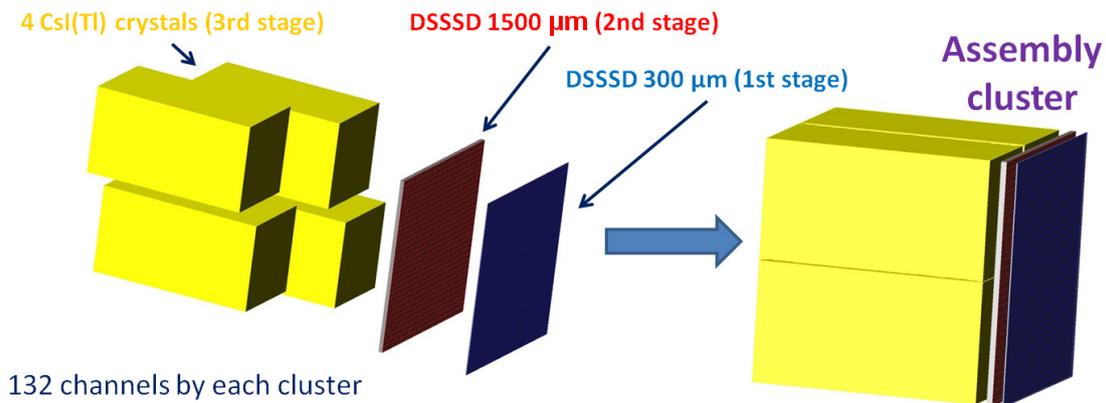


Figure 2. Composition of a Farcos telescope. The Two double-sided silicon strip detectors are followed by 4 CsI(Tl) crystals in a 2x2 configuration.

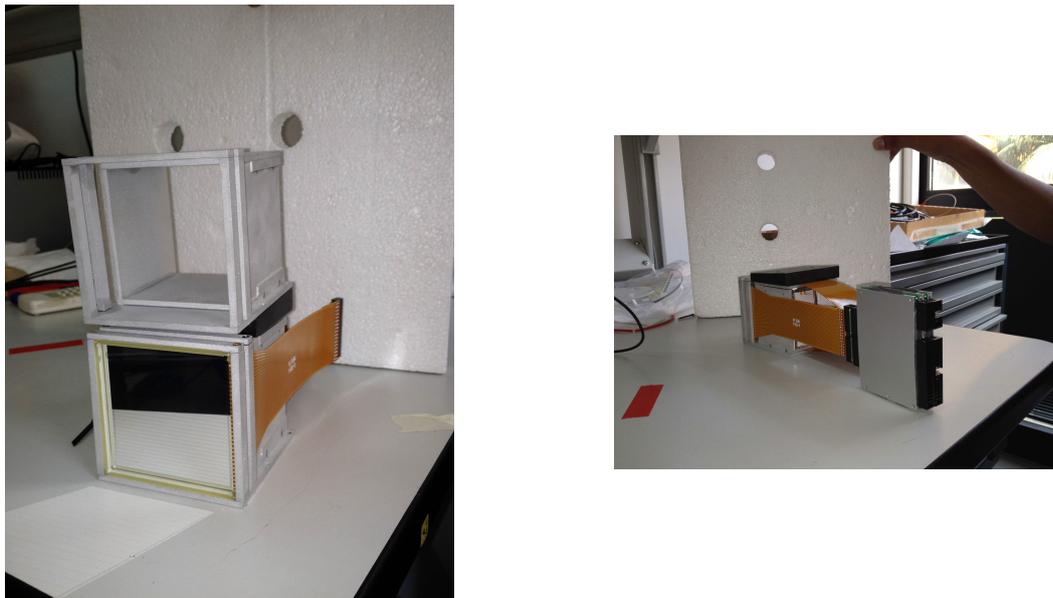


Figure 3. Left panel: The mechanical mounting of Farcos telescopes. Right panel: the back of the telescope with the 32 channel pre-amplifiers.

shown that these devices are characterized by rise-times of 3-7 nsec and energy resolutions of the order of 4.3 KeV when used with input capacitances between 0 and 100 pF. Depending on the experiment, a wide range of sensitivities can be selected, ranging between 5 and 100 mV/MeV. This compact solution is only temporary. Indeed the Farcos array is characterized by a large number of channels and must be used in a wide range of physics cases. Therefore an integrated electronics projects (such as ASIC) but characterized also by a certain degree of flexibility is envisioned. The idea consists of using new electronics standards that would allow digitalization of the signals induced in silicon and CsI(Tl) with the possibility of having a large dynamic range without the necessity of changing hardware. These solutions have supposed to work also in view of the planned transportability of the array that should be used in different laboratories and coupled to different types of devices.

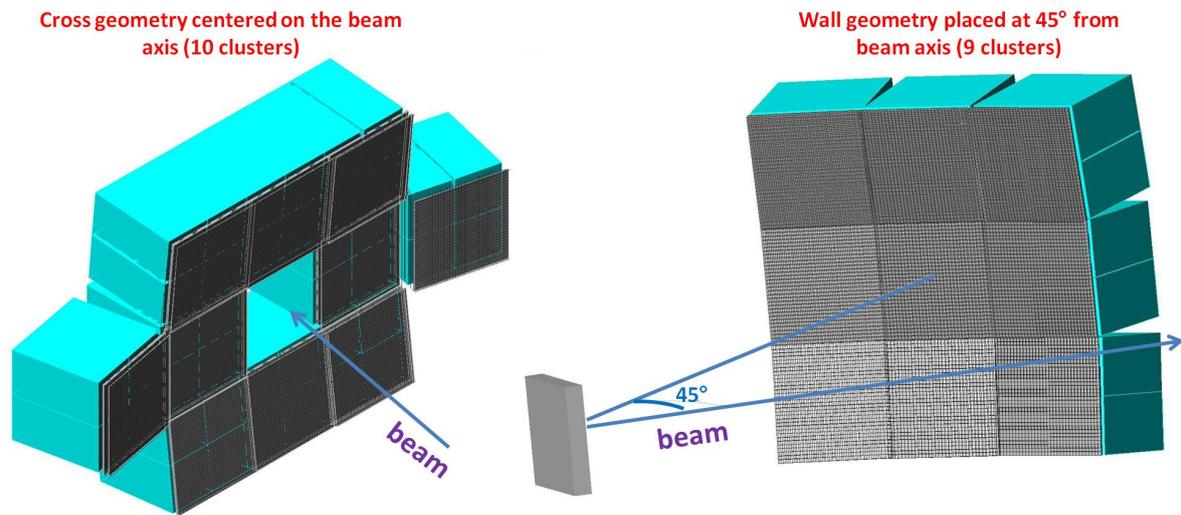


Figure 4. Composition of a Farcos telescope. The Two double-sided silicon strip detectors are followed by 4 CsI(Tl) crystals in a 2x2 configuration.

3. First tests with Farcos detectors

The light output in thallium doped CsI occurs through the transfer of energy in the crystal by the incident ion to the excitation and subsequent radiative decay by both the crystal and thallium dopant ions. The thallium is incorporated into the lattice of CsI detectors of Farcos in molar concentrations of the order 1200-1500 ppm during crystal growth [12]. The light output depends on thallium doping concentration, the temperature and, possibly, other chemical or physical properties of the crystal. The observations of local non-uniformities in light output [13] have been often attributed to non-uniformities in Tl doping concentration. It has therefore been suggested that changes in the growth procedures for the CsI(Tl) crystals, an accurate compensation of the observed non-uniformities, or a combination of these techniques might lead to an improved energy resolution. In other studies [13], however, the origins of the non-uniformities observed are not understood. They may include not only local variations in the thallium doping concentrations but also the presence of crystal defects or contaminants [14]. Understanding these non-uniformities and correcting them is key to obtaining better performances for Farcos. Indeed, in the configuration used for Farcos, the CsI(Tl) crystals represent the most important limiting factor in energy resolution, especially if compared to the silicon strip detectors.

In order to test the position dependence of the response of the CsI crystals to 5.486 MeV alpha particles from a ^{241}Am source, a test apparatus was built, which allows one to move a collimated alpha source and a CsI(Tl) crystal in perpendicular directions inside a vacuum chamber. The configuration was automated such that an energy spectrum was obtained for points separated by a spacing of 2.7 mm on a 3 by 3 Cartesian grid on the front surface of the test crystals. This grid was centered on the crystals. At each grid point, the collimated source irradiated a circular area of the crystal surface for 15 minutes before moving to the next grid point.

In order to determine the relative position of the edges of the detector along the x and y axes with respect to the lower edge of the motorized slides a fit of the spectrum of the counts of the alpha particles, recorded in a fixed time interval (in our case 15 minutes), depending on the position both along the x and y axes have been performed. In fact, the number of the alpha particles that hit the detector are equal to the mean value of the counts recorded when

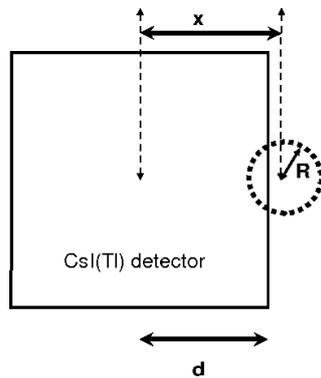


Figure 5. Circular sector intercepted by the alpha source spot on the CsI(Tl) crystal

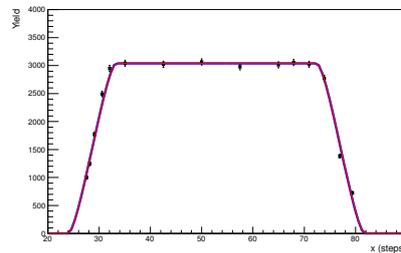


Figure 6. Fit of the distributions of the experimental points along the x axis which represents a specific direction along the surface of the exposed crystal.

the beam spot is completely inside of the detector weighed to the fraction of the circular sector intercepted on the crystal, as shown in 5. It is then possible to fit the distribution of counts of the alpha particles as a function of position by means of the following formula:

$$N(d) = N_0 \left[1 - \frac{1}{\pi} \arccos \left(\frac{x-d}{R} \right) + \sqrt{1 - \left(\frac{x-d}{R} \right)^2} \left(\frac{x-d}{R} \right) \right] \quad (1)$$

when $-1 < \frac{x-d}{R} < 1$, $N(d) = N_0$ when $\frac{x-d}{R} < -1$ and $N(d) = 0$ when $\frac{x-d}{R} > 1$, where d is the edge coordinate of the detector, N_0 the number of hits when the alpha beam spot is entirely on detector and R the radius of the beam spot (all free parameters in the fit procedure). Figure 6 shows the fit of the distributions of the experimental points along the x direction. Similar measurements were done for the other perpendicular y direction. The information extracted with these fit procedures were used to better choose the pixels where to perform tests of the light responses of CsI(Tl) crystals. Using this information we moved the source following a discrete grid in the x-y coordinate plane and mapped the CsI(Tl) response.

At the coordinate $x = i$, $y = j$, the non-uniformity S_{ij} of light output for scintillation crystals is expressed as:

$$S_{ij} = \frac{L_{ij} - \langle L \rangle}{\langle L \rangle} \quad (2)$$

where L_{ij} is the centroid of the energy spectrum at position i, j and $\langle L \rangle$ is the average over the entire crystal. In the case of a crystal with a perfectly uniform response, the variance of S_{ij} would be dominated only by the statistical uncertainty of the centroids of the peaks. In practice, the variance of S_{ij} can be dominated by the light output non-uniformity in each crystal. The centroid of the light output peak was calculated for each of the Cartesian grid points. Figure 5 shows the S_{ij} calculated from Equation 2 for one test crystal.

This crystal on Fig. 7 shows a very good uniformity (better than 1%).

On Fig. 8 we show a crystal where a non-uniformity larger than 5% is observed when moving from one edge to the other. Furthermore, a gradient in the light response is observed as a function of the x-y position on the surface. In the case of non-uniform crystals like the one shown on Fig. 8, it will be important to study the position dependence of light response with higher energy

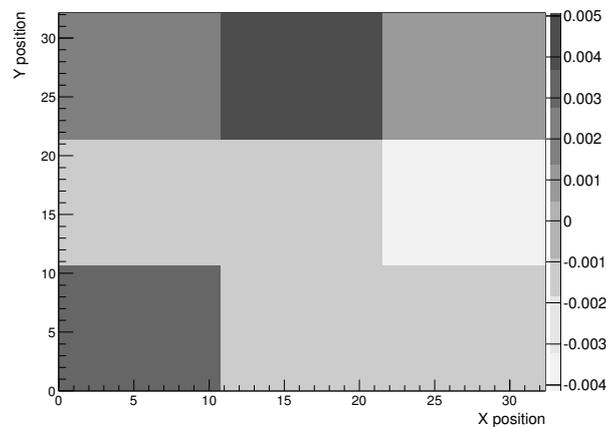


Figure 7. Light response spectra in grey scale for the FARCOS CsI crystal serial number SBG055.

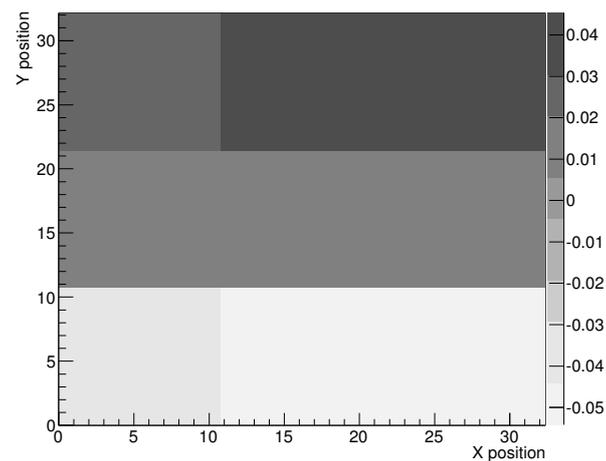


Figure 8. Light response spectra in grey scale for the FARCOS CsI crystal serial number SBG052.

alpha particles injected directly by an accelerator. These tests will be carried out in summer 2012 at the Laboratori Nazionali del Sud of Catania, with the aim of obtaining position-dependent correction factor in light spectra measurements performed by CsI(Tl). With energetic beams it is indeed possible to explore position dependencies in the interior of the crystal, as compared to the case of test performed with low energy alpha particle emitted by radioactive sources.

4. Conclusions and future extensions of the Farcos project

Transport models of nuclear reactions have shown that neutron-proton, neutron-neutron and proton-proton correlation functions are sensitive to the density dependence of the symmetry energy [15]. Measuring these correlation functions is very difficult. Some relevant results have been obtained by the CHIC collaboration using telescopes for charged particles and liquid scintillators for neutrons [1]. The possibility of having high resolution in Farcos and a very good impact and reaction plane selection with Chimera has therefore stimulated the idea of

including neutron detection within Farcos telescopes. In the next couple of months a detector stack solution will be studied with beam tests at the LNS of Catania. Specific details about the neutron detection solution will be tested and established soon. However, a preliminary study seems to suggest that a number of scintillator materials followed by photodiodes and/or segmented silicon detectors may provide tools to identify neutrons as well as determine their kinetic energy and scattering angles.

These features, together with the already existing capabilities with respect to detection of charged particles will represent an important step towards the construction of a device that can be very powerful in the study of nuclear reactions at different beam energies.

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