FAZIA: A VERSATILE DETECTION SYSTEM FOR EOS STUDIES*

Giacomo Poggi

for the FAZIA Collaboration

Università degli Studi di Firenze and INFN Sezione di Firenze, Italy

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In this paper, we describe the main results obtained by the FAZIA Collaboration during its R&D phase devoted to the design of a versatile and modular detector array, meant for a possible 4π angular coverage, necessary for studies of heavy-ion collisions with radioactive nuclear beams. The basic module of the array and the solutions devised to get its final performances are described. The obtained improvements with respect to existing detectors are due to a better understanding of the involved detection mechanisms, to the technical solutions introduced accordingly on the detector material and construction, and to the purposely developed digital techniques for Pulse Shape Analysis. Finally, a significant effort has been dedicated to the Front End Electronics (FEE) and Data Acquisition and Transfer (DAQ). The FAZIA Demonstrator, *i.e.* the first working array composed by the FAZIA basic modules, is now in operation. After its commissioning at LNS, it will be coupled next year with INDRA detector for a physics campaign at GANIL.

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1. Introduction

The goal of the R&D phase of the FAZIA Collaboration has been the design of a versatile and modular detector array, ideally with a 4π angular coverage, necessary for studies of heavy-ion collisions with radioactive nuclear beams. Such studies are basically dedicated to determine the parameters of the Nuclear Equation of State and, in particular, the Symmetry Energy term for conditions far from normal density and temperature. To

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that aim, the detectors must have very good Z and A identification capabilities over a range of energies as wide as possible. In order to reach this goal, a very important effort has been devoted to improving the Pulse Shape Analysis (PSA) techniques in silicon, implemented with a fully digital approach. The basic detection module, whose prototype has been designed and developed during the R&D phase, is described in Sect. 2. In Sect. 3, details are given about the main achievements of this R&D. Simulations of the signal shape behaviour have been performed and served as a guideline for the technical actions for improving PSA performances of the prototype modules. The most important results refer to the study and removal of channelling effects spoiling PSA (and also ΔE–E), and to the evaluation of the silicon doping uniformity necessary to get the desired identification quality. A short paragraph is dedicated to other technical developments and studies performed during the R&D phase. In Sect. 4, a short description is given about other R&D activities, not detailed in this report. The experiments of the R&D phase were performed at the Laboratori Nazionali di Legnaro (LNL), the Grand Accélérateur d'Ions Lourds (GANIL) and the Laboratori Nazionali del Sud (LNS). After the R&D phase, FAZIA decided to assemble a Demonstrator (Sect. 5) necessary to verify the dependability of the adopted solutions on a working detector array during normal experimental conditions under beam. For the Demonstrator, a newly designed electronics has been realized, which is briefly described in the same section. There a brief overview is also given about the commissioning of the Demonstrator at LNS and the next coupling of the Demonstrator with the INDRA detector at GANIL. A very comprehensive presentation about FAZIA R&D can be found in [1].

The FAZIA Collaboration is mainly composed, for the Italian part, by INFN of Bologna, Firenze, Padova, LNL, LNS and Napoli, and by Universities of Bologna, Firenze, Padova and Napoli; for the French part, by IPN Orsay, Université Paris-Sud XI and by LPC, IN2P3-CNRS,ENSICAEN and Université de Caen, GANIL; for the Polish part, by the Heavy Ion Lab., University of Warsaw and by the Jagiellonian University and the Institute of Nuclear Physics IFJ PAN, Kraków.

2. Basic module

The basic detection module, implemented according to the recipes identified thanks to the R&D phase, consists of a three-element telescope. As shown in Fig. 1, the first element is a 300 μm thick silicon detector, while the second module is identical to the first one except for an increased thickness (500 μm). Both silicon detectors are reverse-mounted, *i.e.* the particles enter from the low-field (ohmic) side. The last detector is a 10 cm long CsI(Tl) scintillator, whose fluorescence light is read-out by means of a Si photodiode.

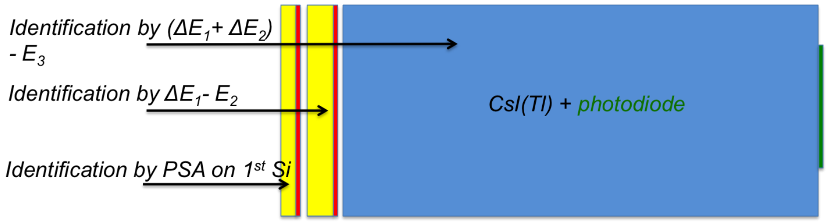

Fig. 1. The basic FAZIA module. The arrows represents particles of different energies which are identified in the way reported over the relevant arrows.

This seemingly standard configuration actually includes very important and non-standard features which are described with some details in the next section and are here simply listed: the silicon material of the first two elements is a neutron Transmutation Doped (nTD) material, having a resistivity of the order of 2–3 k$\Omega\times$ cm, with a uniformity of about 4% or better; furthermore, the nTD silicon wafers used for manufacturing the detectors are cut from a $\langle 100\rangle$ crystal along selected orientations, necessary for avoiding channelling effects.

3. PSA and ΔE–E identification

In order to reduce the energy threshold for Z and possibly A identification of particles stopped in the first silicon detector, special attention was devoted to improve PSA techniques (see [2] and references therein).

Particle identification by PSA is usually obtained (see Fig. 2) in a reverse-mount Si by correlating energy with rise-time of the charge signal. At a given total energy, the heavier the particle, the longer the rise-time. In fact, PSA is basically possible because the time evolution of the signal (tens of ns) due to a ionizing particle also depends on the ionization density along the track: in fact, a high density of ionization hinders the immediate erosion of the electron-hole column, an effect known as Plasma Delay.

Simulations were soon developed [4], because only by understanding the details of the physical processes involved in the signal formation one could hope to optimize the detection technique. Deeper simulations were also implemented in the following years [5, 6]. One of the most direct results, and frankly not unexpected, is that for a stable signal response, a uniform electric field inside the detector is mandatory, *i.e.* the doping uniformity of silicon is a very critical issue. For these reasons, FAZIA developed a system to test the doping uniformity of available silicon materials. Figure 3 shows the resistivity map of a Float Zone (FZ) silicon as well as the apparatus used to extract such an information [7]. The shown map corresponds to a non-uniformity of the order of 15–20%, a value typical for FZ material. Similarly obtained maps for nTD silicon showed value of the order of few percent. Consequently,

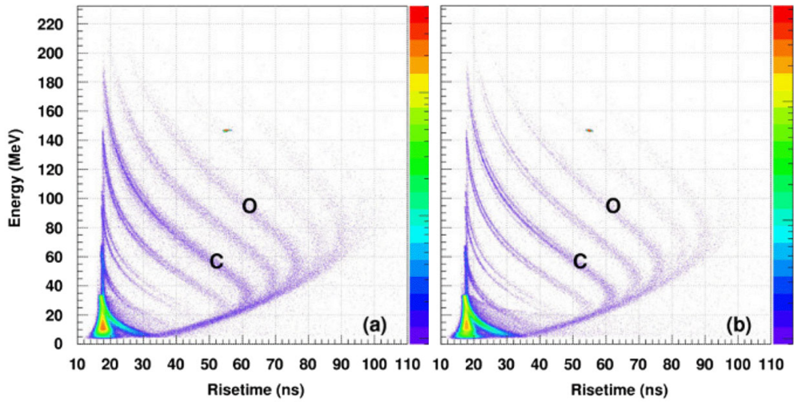

Fig. 2. Pulse shape identification obtained by plotting the energy of a stopped particle in the silicon detector as a function of the risetime of the charge signal. Parts (a) and (b) differ for crystal cut orientation, as described in the following and in [3].

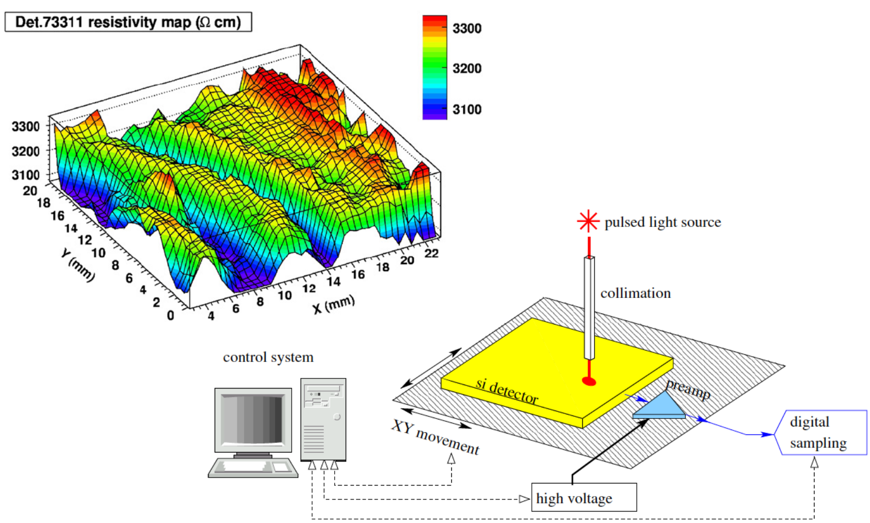

Fig. 3. In the upper left-hand side, a resistivity map of an FZ silicon detector is reported. The map has been obtained with the apparatus shown in the lower right-hand side of the picture. For details, see [7] .

the collaboration decided to use nTD silicon. Typical values of the uniformity of presently used FAZIA detectors is better than 6%. Experiments were performed using charge and current preamplifiers purposely designed [8] and during these early experiments, we were faced with another important issue:

channelling effects and their influence on PSA performances. The problem arose during the very first phase of R&D when strong fluctuations were observed in the PSA of heavier ions. Also thanks to a preceding experience [9] gained in the field of channelling in silicon detectors, the problem was pretty soon recognized. The adopted solution has been obtained [3] by finding the proper orientation of the cut of $\langle 100 \rangle$ wafers which guarantees a very stable PSA response of the detectors (the so-called "random" orientation cut). An example of the improvement by proper orientation of the silicon is appreciated in Fig. 2: while the left-hand side (part (a)) of the figure shows the correlation observed when the crystal of the silicon detector is oriented in a standard way, *i.e.* perpendicular to the direction of the impinging particles, the right-hand side (part (b)) shows the same correlation when the silicon detector is tilted by an angle corresponding to "random" incidence.

The much better identification presented in part (b) clearly demonstrates the effectiveness of such an orientation. All silicon detectors presently used in FAZIA are, therefore, obtained from wafers of high uniformity $\langle 100 \rangle$ nTD silicon, cut along the proper "random" direction. As soon as the detectors manufactured according to these recipes were available, a series of experiments were performed at LNS, dedicated to verifying the identification performances. The results are summarized in Fig. 4 (for PSA) and Fig. 5 (for ΔE–E), and were obtained by detecting the nuclear fragments produced in

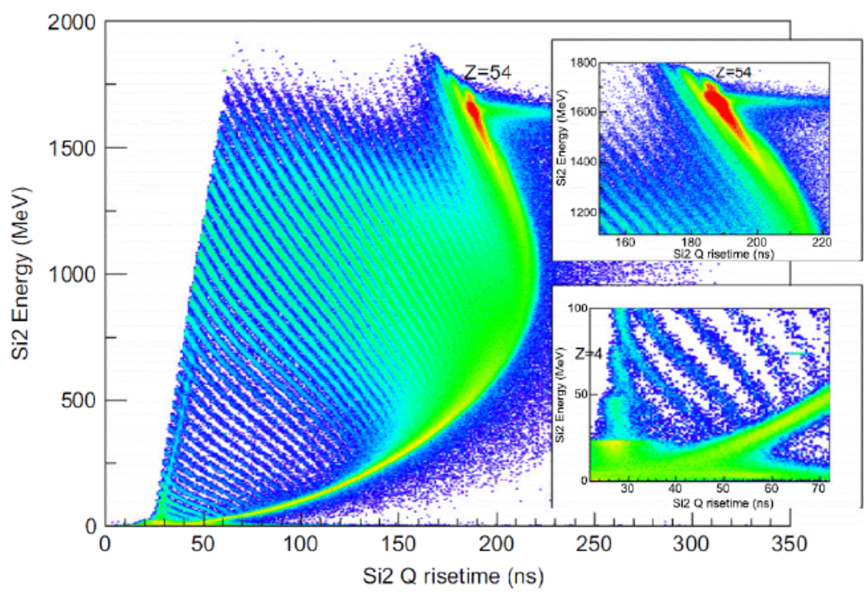

Fig. 4. PSA correlation: energy *vs.* rise-time of charge signal for nuclear fragments stopped in a FAZIA silicon 300 μm thick. In the insets, expansions of the regions of light particles and elastic scattering are reported. From [1].

the reaction ^{129}Xe+^{58}Ni @ 35 MeV/n. The Z and A identification shown in both figures confirms that the FAZIA R&D has been indeed able to produce a real step forward in the field. Details of these performances can be found in [10] and [11].

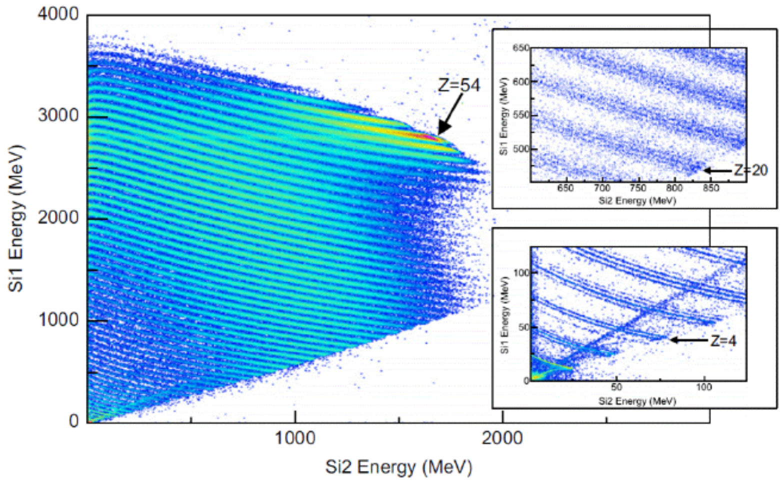

Fig. 5. ΔE–E correlation using two FAZIA silicon detectors. The insets represent expansions around $Z = 4$ and $Z = 20$. From [1].

A very important point for defining the Z and A identification performances is to quantify the energy thresholds. As a general criterion, FAZIA adopted the Figure of Merit [12] (FoM in the following) for adjacent peaks in the obtained Particle Identification spectra: two equal-intensity peaks are separated if FoM > 0.7 [1]. Figure 6 reports these thresholds. Squares (red) represent the energy threshold associated to Z identification with ΔE–E technique determined by the thickness of the first silicon (300 μm); these values are reported only for comparison with the actual, much lower threshold of the PSA technique (diamond, in blue). Z identification thresholds attainable with a ΔE detector 20 μm thick are also reported as crosses for further comparison. As far as energy thresholds for mass (A) identification are concerned, triangles (green) represent the values reached using ΔE–E techniques. As discussed in [10], these thresholds are very close to the limit imposed by the energy straggling on silicon. Also reported as circles (purple) are the thresholds for A identification observed by means of a recently [13] optimized PSA procedure (see also the next section). Please note that although for $Z < 6$ threshold values are not reported in the figure, all those particles are identified in terms of Z and A by means of PSA. In general, one observes for both ΔE–E and PSA procedures performances of an unprecedented quality.

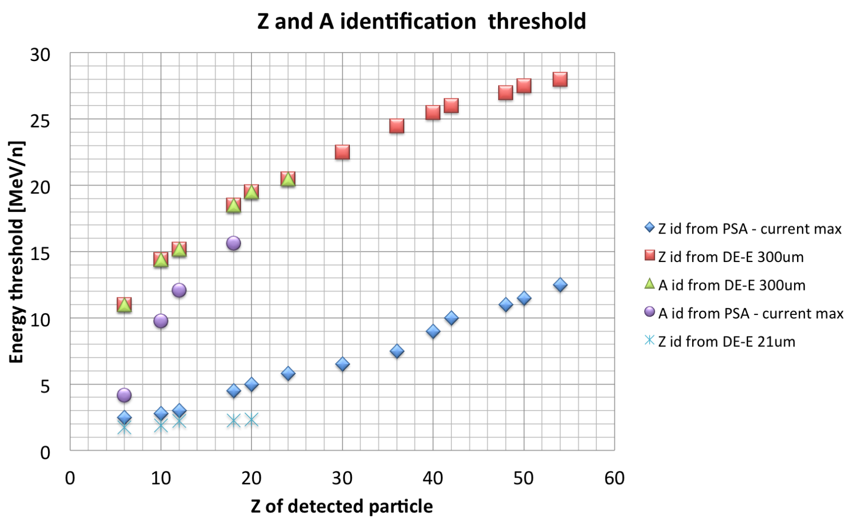

Fig. 6. Energy thresholds for Z and A identification of FAZIA detectors. For details, see the text.

In this respect, it is worth to mention that the experiments performed during the last period of FAZIA R&D confirmed that the best Z and A identification with PSA is obtained according to an early-found recipe [14], *i.e.* the correlation of the energy of the stopped fragment with the maximum of the current signal. The A identification thresholds with PSA reported in Fig. 6 have been obtained indeed by means of this correlation.

4. Other R&D studies

During FAZIA R&D many other items were addressed, all connected to the detection performance and optimization. Among them it is worth mentioning:

1. Digital timing and energy measurements. New digital techniques for timing and energy determination were soon developed by the collaboration and were adopted in the following implementation [15–17].
2. Thin layers of aluminum ($\approx 30\,\mathrm{nm}$) on both silicon surfaces are provided to keep at very low level the sheet resistance, thus optimizing timing.
3. Single Chip solution. The second silicon detector can act both as ΔE detector and photodiode to read CsI(Tl) fluorescence [18].
4. Funneling in underbiased silicon detectors. When the first silicon detector is underbiased, the energy deposited by particles punching through the firstly traversed undepleted region is correctly measured

and mass discrimination improves at the expenses of a significantly longer response time [19].

5. Study of radiation damage effect on silicon for PSA application. Limits for irradiation fluences have been found in order to determine safe operation during commissioning [20].
6. Test beams have been dedicated to verifying FAZIA performances with a 21 μm thick ion implanted epitaxial silicon detector fabricated using a low temperature technique [21].

5. The FAZIA Demonstrator and electronics

After the R&D phase, FAZIA entered the Demonstrator Phase, where single telescopes are arranged in the final configuration. The structure of the array consists of blocks, each containing 16 telescopes. Severe mechanical tolerances are necessary in order to keep out channelling effects on all detectors. Figure 7 shows a block of 16 telescopes connected to its electronics. The electronics consists of a Front End card (FEE) and other "ancillary" cards, necessary for data transmission and slow controls. The blocks are mounted under vacuum, so that proper water cooling is provided. Each block communicates with the outside through a unique fast fiber optics. Beside this connection, there is only one copper line providing a 48V power supply. The FEE includes the preamplifiers, the ADCs and the FPGA necessary for data elaboration, temporary storage and de-randomization.

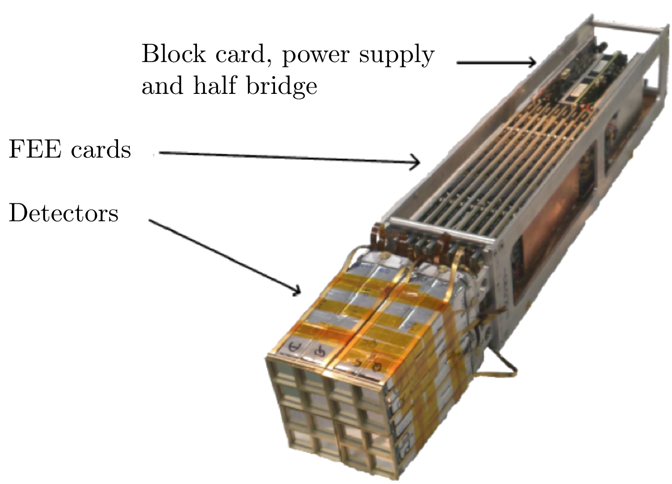

Fig. 7. The FAZIA Demonstrator. In the figure, one of the 12 blocks of the Demonstrator is shown, containing 16 telescopes and all the relevant FEE and ancillary electronics.

Although some physics results have been already obtained in experiments performed with the detector prototypes [22, 23], the true physics campaign with FAZIA started only recently and consists of a series of experiments approved by the PAC of LNS. In these experiments, only 4 or 6 blocks out of the final 12 blocks of the Demonstrator will be used. The Demonstrator will operate with all blocks coupled with the INDRA multidetector at GANIL, starting from 2017 (see Fig. 8).

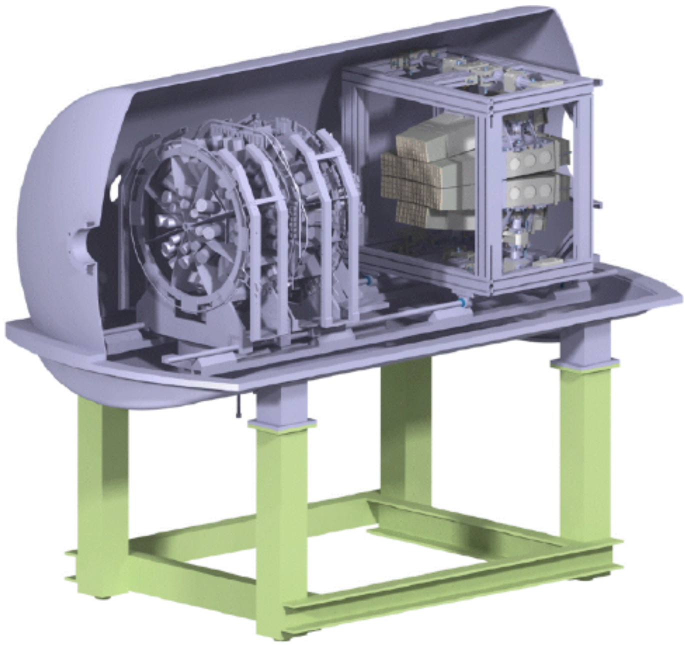

Fig. 8. The FAZIA Demonstrator coupled to INDRA multidetector. The system will begin commissioning by 2017.

6. Conclusions

The R&D activity developed by FAZIA permitted to reach the original goal of the collaboration, *i.e.* the construction of a detector having Z and A identification performances definitely better with respect to existing apparatuses. The major technical advances refer to:

1. extended application of PSA with very uniformly doped nTD silicon,
2. proper cut of silicon wafers in order to avoid channelling effects in the detectors, with benefit for both PSA and ΔE–E,
3. careful control of applied voltage on silicon detectors in order to keep the electric field constant in time, very important for PSA usability,

4. very good planarity and constant thickness of transmission type silicon detectors, mandatory for best ΔE–E performance,
5. thin layer of aluminum on both silicon surfaces to keep at very low level the sheet resistance on silicon, thus optimizing timing,
6. fast and low noise preamplifiers closely connected to the detectors, placed under vacuum,
7. extensive optimization of digital treatment of the signals.

The FAZIA Demonstrator is now taking data by running experiments at LNS and will be moved soon to GANIL, where it will be coupled with the multidetector INDRA.

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