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**Limitations of the Pulse-Shape Technique
for Particle Discrimination in Planar Si
Detectors**

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Limitations of the Pulse-Shape Technique for Particle Discrimination in Planar Si Detectors

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Abstract

Limitations of the pulse-shape discrimination (PSD) technique – a promising method to identify the charged particles stopped in planar Si-detectors – have been investigated. The particle resolution turned out to be basically determined by resistivity fluctuations in the bulk silicon which cause the charge-collection time to depend on the point of impact. Detector maps showing these fluctuations have been measured and are discussed. Furthermore we present a simple method to test the performance of detectors with respect to PSD. Another limitation of the PSD technique is the finite energy threshold for particle identification. This threshold is caused by an unexpected decrease of the total charge-collection time for ions with a short range, in spite of the fact that the particle tracks are located in a region of very low electric field.

I. INTRODUCTION

Recent investigations demonstrated that pulse-shape discrimination (PSD) can be applied to identify the charge and even the mass numbers of charged particles hitting the rear side of totally depleted (n-type) Si-detectors [1]. This method exploits the dependence of the plasma-erosion time and the drift time of charge carriers (electrons and holes) on the electric field distribution inside the detector, and on length and density of the ionization track. Both effects cause an increased charge-collection time t_{cc} if the ionization track is shorter and more dense. Particle discrimination becomes possible by measuring a parameter which is related to t_{cc} , i.e. by analysing the pulse shape. The most convincing results have been obtained with the zero-crossing method [1]. We plan to exploit this technique in a 4π Si-detector array for charged-particle detection inside the European γ -ray facility EUROBALL. The EuroSiB array will consist of hexagonal and pentagonal Si slices of 500 μm thickness and $\approx 1300 \text{ mm}^2$ active area, glued onto thin ceramics backings which form a selfsup-

porting 42-element polyhedron. The essential design goal is to combine the advantage of a compact, low-mass Si ball – little absorption and scattering of γ rays – with an efficient detection and identification of evaporated protons and alpha particles in the full energy range. Excellent p/α separation down to low energies of $\approx 2 \text{ MeV}$ is decisive for the main application – the exit-channel selection in nuclear-structure experiments. Therefore it is very important to understand the effects which degrade the particle resolution, and to develop simple procedures for testing the detector performance. Corresponding investigations have been performed and are discussed in this paper.

The finite energy threshold for particle discrimination represents another limitation of the PSD technique, in particular for applications in the fields of heavy-ion physics or ion-beam analysis of solids (e.g. ERDA). In a beam experiment we investigated the reason for this lower discrimination threshold and demonstrated the present limits.

II. PARTICLE RESOLUTION

A. Beam Experiments

In the context of the EuroSiB project we had to develop a compact front-end electronics and to test the particle resolution with the large-area prototype detectors. For this purpose we performed test experiments at the VICKSI accelerator in Berlin. Experimental conditions were chosen in correspondence with typical nuclear-structure experiments. We bombarded a 2 mg/cm^2 Ni target with a 150 MeV ^{36}Ar beam up to 5 pnA. A high voltage of 20 kV was applied to the target ladder to suppress δ -electrons. Various Si detectors including prototypes for EuroSiB were arranged in a vacuum chamber with the low-field (rear) sides facing the target, and exposed to the light charged particles (LCP) produced in fusion-evaporation reactions. For each event in a single detector we measured simultaneously the energy deposition E , and the zero-crossing time t_{zC} of a bipolar signal derived from the charge pulse of the preamplifier by means of two successive differenti-

ations ($\tau_{RC} \approx 200$ ns) [1]. The protons and alpha particles are identified in a plot of t_{ZC} versus E where each of the ion species is characterized by a specific correlation $t_{ZC}(E)$. Two points turned out to be of great importance for a good particle discrimination:

(i) The detector bias U_D has to be carefully optimized. The p/α resolution is considerably enhanced if the detector is operated with a bias slightly below the depletion voltage which is extracted from the dependence of the detector capacitance on U_D .

(ii) The load resistor R_L of the preamplifier has to be small to minimize the voltage drop $\Delta U_D = R_L \cdot i_L$ caused by the leakage current i_L of the detector. The leakage current of EuroSiB prototype detectors was typically 20 nA without load but increased up to ≈ 300 nA at high load (small target-detector distance, high beam current). This is due to a huge rate of low-energy X-rays which are produced in the target and absorbed in the detector. A modulation or variation of the beam intensity varies i_L and consequently the effective bias voltage U_D at the detector, which degrades the particle resolution [1]. The preamplifier developed for EuroSiB is distinguished by a small R_L of only $2\text{ M}\Omega$, thus keeping this effect small ($\Delta U_D/\Delta i_L = 0.2\text{ V}/100\text{ nA}$).

Fig. 1 shows a particle discrimination plot measured with a prototype of the EuroSiB front-end electronics and with an EuroSiB prototype detector at realistic experimental conditions. The detector was mounted at $\theta = 117^\circ$ with respect to the beam axis, the detector-target distance ($d = 64$ mm) corresponds to the EuroSiB geometry. The quality of particle discrimination is sufficient for a p/α separation in the full energy range of the evaporation spectra.

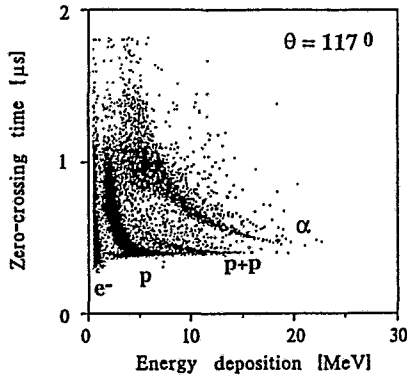


Fig. 1 Particle-discrimination plot measured with an EuroSiB prototype detector (Table 1) and a prototype of the EuroSiB front-end electronics at a count rate of ≈ 4 kHz.

On the other hand we got much better results with other detectors. The right panels of Fig. 2 compare for example the (t_{ZC}, E) plots measured at lower count rates of ≈ 500 Hz with a "reference" detector used in many tests before, and an EuroSiB prototype detector, both positioned at $\theta = 110^\circ$. The detector data are summarized in Table 1. For practical applications it is therefore important

to understand the reason of these differences, and to select detectors of a sufficient quality.

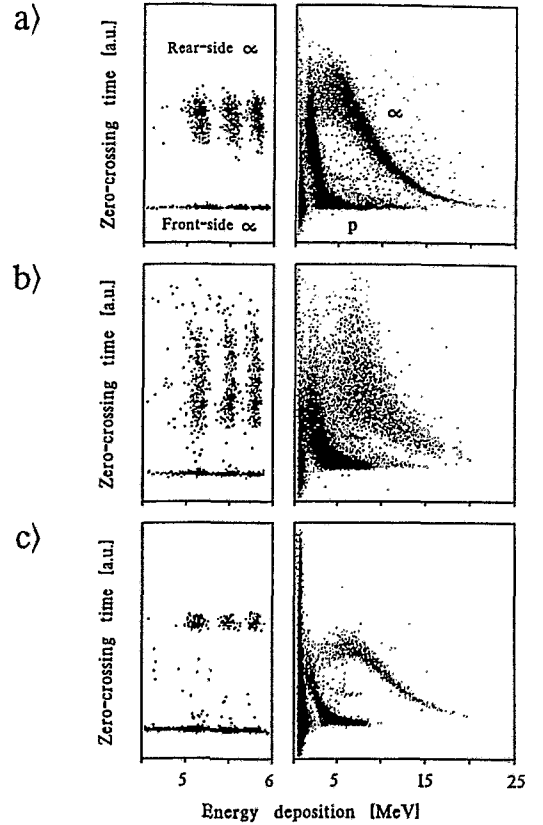


Fig. 2 Correlation of detector tests exploiting mixed-nuclide α sources (left panels) with results of beam experiments at low count rates (right panels, see text and Table 1):

- a) Reference detector Eurisys IPH 450-500-20 TM;
- b) EuroSiB prototype H (hexagon), totally exposed;
- c) EuroSiB prototype H, spot of 2 mm diameter exposed.

B. Testing the Detector Performance

A procedure for testing a large number of detectors without expensive beam experiments is absolutely necessary for projects like EuroSiB. We found no significant correlation between the detector performance with respect to PSD and certified detector characteristics like resistivity, energy resolution, or the dependence of the detector capacitance on the bias voltage. To obtain a useful parameter we decompose the zero-crossing time in a sum $t_{ZC} = t_0 + t_q$, where t_0 means the zero-crossing time which would correspond to an immediate detector response and t_q the zero-crossing shift caused by the charge-collection time. The spread of t_q for monoenergetic particles, δt_q , related to the mean value $\langle t_q \rangle$, is expected to be a measure of the detector performance. Since t_0 can be easily measured, e.g. by means of a pulse generator, it is possible to extract the "quality" parameter $Q = \delta t_q / \langle t_q \rangle$ from t_{ZC} distributions measured with α particles from a radioactive source.

Table 1
Parameters of two detectors used in our tests

Detector Type	Reference IPH 450-500-20 TM	EuroSiB Prototype H (Hexagon)
Manufacturer	EurisyS Measures	
Structure	Implanted p ⁺ -n-n ⁺ structure, Al contacts	
Dead zone	≈ 3000Å Si-equivalent at the rear side	
Thickness	500μm	500μm
Active area	450 mm ²	1300 mm ²
Optimum bias	120 V	≈ 60 V

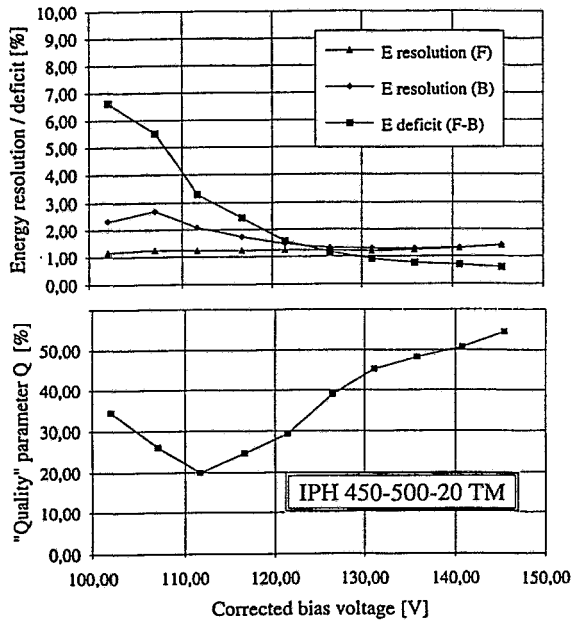


Fig. 3 Typical dependence of the particle resolution (quality parameter Q , see text), the energy resolution, and the energy deficit on the detector bias. The data were measured for 5.8 MeV alphas with the reference detector (cf. Table 1).

To test a detector, we expose the rear side as well as the front side simultaneously to alpha particles from ^{239}Pu - ^{241}Am - ^{244}Cm sources. If the range of these alphas in Si (25-30 μm) is small compared to the detector thickness, the front-side alphas are stopped in the high-field region which results in an almost negligible charge-collection time. The corresponding signals are used instead of a pulse generator as a reference for fast charge collection. As expected, the front-side (α_F) and rear-side (α_R) events are clearly separated in the measured (t_{ZC}, E) plots (Fig. 2, left panels). Now we can extract the quality parameter

$$Q = \frac{\delta t_q}{\langle t_q \rangle} = \frac{\delta t_{ZC}(\alpha_R)}{\langle t_{ZC}(\alpha_R) \rangle - \langle t_{ZC}(\alpha_F) \rangle}$$

as well as other parameters like the energy resolution $\delta E(\alpha_R)$ for rear-side events, and the energy deficit $\Delta E = E(\alpha_F) - E(\alpha_R)$. This difference between the energies measured for the α_F and α_R is due to possible dead layers near the rear contact, due to the increased recombination and trapping losses in the case of slow charge collection

dominated by the drift of holes, and due to a possible ballistic deficit. Furthermore, the α sources can be (partially) covered with thin moderator foils to produce quasi-monoenergetic alpha lines down to energies below 2 MeV and to study the detector performance as a function of the particle energy. We have used this method to optimize the detector bias and to set up the front-end electronics.

Some results for the EuroSiB prototype and the reference detector are shown in Figs. 2-3. Fig. 2 demonstrates that the results of the source test are indeed consistent with the p/α resolution achieved in beam experiments. This fact has been confirmed for a large set of different detectors (thickness 50 to 500 μm, active area 50 to 1300 mm², surface-barrier type or implanted p⁺-n-n⁺ structure) used in experiments at the VICKSI beam. Fig. 3 shows a typical dependence of the separation quality Q , the energy resolution δE , and the energy deficit ΔE , on the detector bias. The maximum particle resolution (i.e. a minimum value of Q) can be achieved with a low bias, but on the expense of a degraded energy resolution and a larger energy deficit.

C. Detector Scanning

In a second step we scanned detectors with a collimated ^{239}Pu - ^{241}Am - ^{244}Cm source, thus exposing only selected spots to the alpha particles. With apertures of 1-2 mm diameter we found spots characterized by a surprisingly small spread $\delta t_{ZC}(\alpha_R)$ (Fig. 2c, left panel). The average zero-crossing time $\langle t_{ZC}(\alpha_R) \rangle$ varied across the detectors. In a cross-check at the beam we placed an aperture of 2 mm diameter in front of the EuroSiB prototype detector. In correspondence with the source test we observed sharp proton and alpha lines for some spot positions (Fig. 2c, right panel), shifted and/or broadened lines for other exposed regions. The detectors must therefore consist of distinct zones with different charge-collection times for a given ion species and energy. Previous experimental studies exploiting a light-scanning technique [2] correlate such fluctuations with inhomogeneities of the resistivity in the bulk silicon. A comparison of (t_{ZC}, E) plots corresponding to total exposure and spot irradiation of the same detector (Figs. 2b and 2c) demonstrates clearly that the quality of particle discrimination is not limited by the electronics resolution, but by these inhomogeneities.

D. Detector Mapping

Some of the large-area detectors were mapped in order to investigate the geometrical structure of these resistivity fluctuations. We placed a double-grid avalanche counter (DGAC) between the detector to be investigated and a ^{239}Pu - ^{241}Am - ^{244}Cm source. The DGAC – a gas-filled transmission counter of 5 × 5 cm² active area with thin mylar windows, two sensing-wire planes for the x and y coordinates, and a common cathode [3] – determines the position of penetrating alpha particles with a resolution of $\delta x \approx \delta y \approx 2$ mm. The energy loss for the 5-6 MeV alphas is

only about 800 keV. The hit coordinates (x, y) as well as the parameters t_{ZC} and E obtained from the Si detector were simultaneously recorded for each event. By means of cuts in the (t_{ZC}, E) plane we selected events with large, medium, or short charge-collection time t_{cc} , respectively (Fig. 4a). The (x, y) distributions of the corresponding events visualize detector regions which are distinguished by a different average t_{cc} (Fig. 4b).

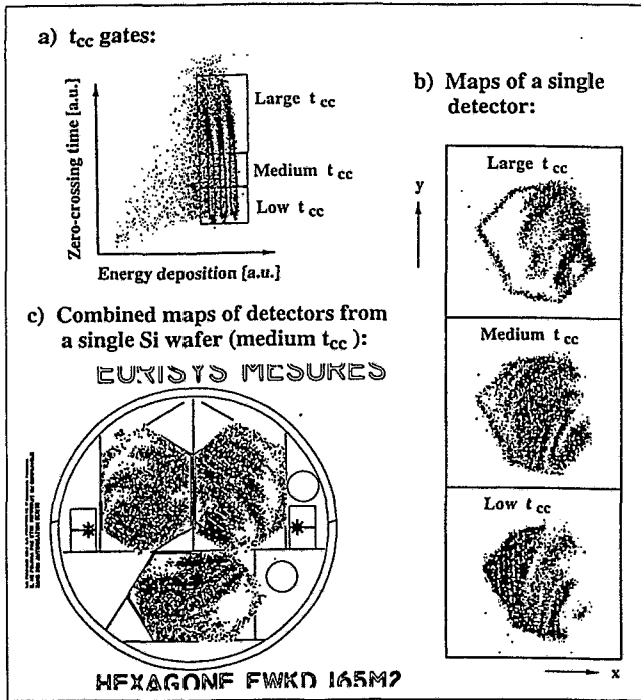


Fig. 4 Mapping results for hexagonal EuroSiB detectors exposed to α particles: Cuts for low, medium, and large charge-collection time are defined in the (t_{ZC}, E) plot (a). Scatterplots of the corresponding hit coordinates (x, y) visualize detector regions of fast, medium, or slow charge collection (b). The structures correspond roughly to concentric rings around the wafer center (c).

The measured maps demonstrate that events resulting from hits near the detector edges are characterized by a large t_{cc} (Fig. 4b). This is an expected effect caused by the fringing field. However, the dominating structures on the detector are approximately shaped like concentric rings with a width of typically a few millimeters. By joining maps of detectors produced on a common wafer according to their positions on the wafer we could show that (i) the concentric structures are roughly centered around the wafer center, and (ii) the ring structure is superimposed by a trend to larger t_{cc} in the wafer center and lower t_{cc} at the periphery. Fig. 4c shows for example the maps of hexagonal EuroSiB detectors corresponding to medium t_{cc} , arranged on the wafer mask. These observations are consistent with the assumption that the spread of t_{cc} is due to an inhomogeneous distribution of impurities which results from the production process of high-resistivity sili-

con. The concentric structures may be caused by a radial temperature profile and distinct recrystallization zones in the floating-zone process. On the other hand, the diffusion profile in the liquid phase diminishes the dopand concentration near the periphery of the grown crystal. In a depleted detector with fixed bias, a lower dopand concentration results in a higher electric field at the rear side and thus in a reduced charge-collection time for ions stopped near the rear side [1]. This is just the observed effect.

We conclude that the homogeneity of the dopand concentration (resistivity) in the silicon crystals used for detector production is a key parameter for the quality of particle discrimination based on PSD. Up to now, the obtained results are far from possible limits. The discrimination plot measured for spot irradiation (Fig. 2c) indicates what a resolution could be achieved with homogeneous detectors. A first step of improvement is expected from detectors made of neutron-transmutation doped silicon which we intend to test in the context of the EuroSiB project.

III. LOWER DISCRIMINATION THRESHOLD

Further effort was made to understand the lower energy threshold of particle identification. We exposed a Si-detector telescope consisting of a $50\mu\text{m}$ ΔE detector and the $500\mu\text{m}$ reference (E) detector (cf. Table 1), both in reverse mount, to intermediate-mass fragments produced in the reaction ^{36}Ar (510 MeV) + [C+Al+Ni+Au]. Pulse-shape discrimination was applied to both detectors. For the E detector we measured t_{ZC} and E with the usual electronics scheme. For the ΔE detector we applied the stretcher method [1] which is based on a simultaneous measurement of the energy deposition (ΔE) and the amplitude A_{Str} of the differentiated charge signal. The telescope arrangement allowed to identify the ions stopped in the E detector by means of the $\Delta E-E$ method, and thus to analyse $t_{ZC}(E)$ correlations for distinct ions down to energies below the PSD threshold. The full (t_{ZC}, E) plot and correlations gated on selected ions are shown in Fig. 5. In contrary to simulations [1], the measured $t_{ZC}(E)$ lines are not monotonous but show a maximum at an energy E_c which corresponds for all of the analyzed ion species (He to Mg) to a range of $R_c \approx 50\mu\text{m}$. Below E_c , the zero-crossing time diminishes with decreasing energy. This effect causes an overlap of the distinct $t_{ZC}(E)$ lines and defines the energy threshold for particle discrimination.

A decrease of t_{ZC} could be caused by a systematic shift of the trigger points defining t_{ZC} for small signal amplitudes. The effect was checked by feeding pulse-generator signals of a defined rise time (20 ns - 2 μs) but variable amplitude into the test input of the preamplifier, and found to be present but not dominating. This fact was confirmed by measuring $t_{ZC}(E)$ curves with different shaping-time constants ($\tau_{RC} = 200\text{ ns} - 2\mu\text{s}$) and with different bias voltages at the E detector (changed average signal rise-time τ_r). In spite of very different ratios of τ_r/τ_{RC} we found the maxima of t_{ZC} at almost unchanged positions E_c .

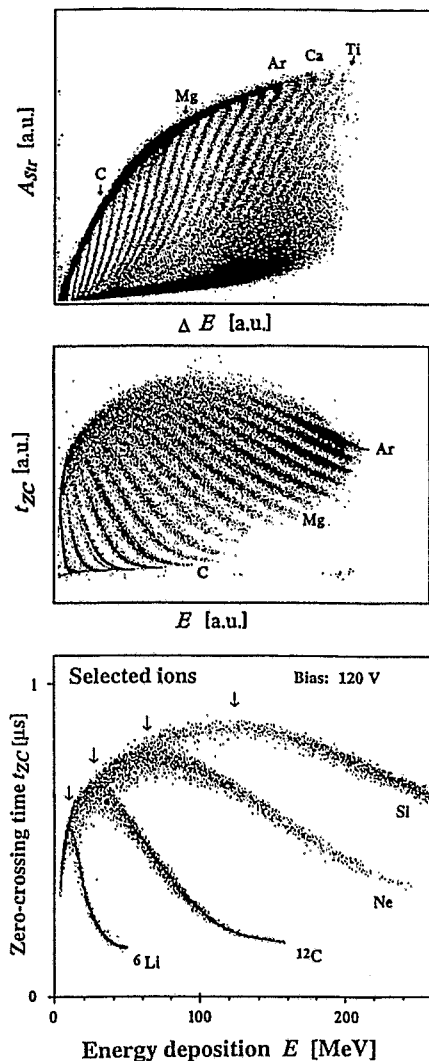


Fig. 5 Particle discrimination plots measured with the Si detectors of a telescope arrangement (see text for details):

- a) Stretcher method ($50\ \mu\text{m}$ ΔE -detector)
- b) Zero-crossing method ($500\ \mu\text{m}$ E -detector)
- c) Selected particle lines from b)

We conclude that the decrease of t_{zC} below E_c is caused by a reduced charge-collection time for short ionization tracks. It seems to be obvious to correlate this effect with an experimental observation of Bohne *et al.* who found the well-known $1/F$ scaling of the plasma delay for heavy ions only down to a critical (effective) field strength F_c , but a saturation or even decrease of the plasma time for $F < F_c$ [4]. For detectors in reverse mount, the effective electric field acting on the ionization track diminishes in fact monotonously with decreasing penetration depth R (cf. ref. [1]), which suggests to correlate R_c with the critical field F_c . However, in this case one would expect a smaller R_c (i.e. lower PSD thresholds) for a higher detector bias. This is in contradiction to our observations.

By applying PSD to the $50\ \mu\text{m}$ ΔE detector we obtained element identification up to ^{24}Cr , limited by the poor statistics for ions with higher charge numbers Z (Fig. 5a). The energy thresholds for Z identification correspond to a track length of only $\approx 25\ \mu\text{m}$. The critical range R_c depends obviously on detector parameters. Further effort is necessary to understand the underlying physical effects.

IV. SUMMARY AND CONCLUSIONS

A compact silicon ball for charged-particle detection inside the European γ -ray spectrometer EUROBALL is under construction. In the context of this project we investigated present limits of the pulse-shape discrimination technique with Si detectors, which is planned to be applied for particle identification.

The achievable quality of particle discrimination varies from detector to detector and is obviously determined by material inhomogeneities, i.e. by resistivity fluctuations in the Si wafers. Such fluctuations disturb also the timing properties of Si detectors [5]. It is therefore a serious task to improve the quality of commercially produced high-resistivity silicon. We presented simple techniques which allow to characterize material inhomogeneities and to test the detector performance with radioactive sources.

The finite energy threshold of particle discrimination is due to an unexpected decrease of the charge-collection time for ionization tracks which are shorter than a critical range R_c . This effect results in overlapping particle lines. We found values of $R_c \approx 50\ \mu\text{m}$ and $R_c \approx 25\ \mu\text{m}$ for detectors of $500\ \mu\text{m}$ and $50\ \mu\text{m}$ thickness, respectively. Further effort is necessary to interpret the experimental findings.

In summary, we conclude that pulse-shape discrimination is not only a promising method for particle identification, but also a simple and powerful tool to investigate properties of semiconductor materials and to study details of the charge-collection process in radiation detectors.

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