Particle identification via pulse shape analysis for large-area silicon detectors of the CHIMERA array


Abstract—Mass and atomic-number identification (ID) of reaction products is a fundamental requirement of any nuclear reaction study. An effective particle-ID method is demonstrated, based on pulse shape analysis/discrimination (PSD) applied to large-area, single-element silicon detectors. This technique uses commercial electronic modules and achieves atomic number resolution rivaling that typically obtained with multi-element (AE–E) detector telescopes. The method is applied to the CHIMERA detector system without compromising its time-of-flight (TOF) resolution. In-beam tests of the PSD method have been performed with large-area, 300-μm thick CHIMERA silicon detectors, measuring particles from the $^{19}$F + $^{12}$C reaction at Tandem energies. Performance of a simple PSD set up is discussed, for front and rear particle injection.

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I. INTRODUCTION

In heavy-ion reaction studies, it is important to characterize reaction products according to mass (A), charge (Z), and energy (E). Precise mass and charge determinations of particles from compound-nucleus or direct reactions achieved in early nuclear heavy-ion reaction studies at low bombarding energies (E/A<10 MeV) have been instrumental in the elucidation of the underlying reaction mechanism [1-2]. In the more recently explored domain of heavy-ion reactions at Fermi or intermediate bombarding energies (10 MeV< E/A< 100 MeV), an accurate characterization of reaction fragments according to their A and Z (or their N/Z ratio) has become perhaps even more important. Here, one is interested in comparing the isospins $I = (A-2Z)/2A$ of fragments formed at lower or higher matter densities to those of particles produced at the normal nuclear matter density [3-4]. Emphasis on isospin transport in much of contemporary and planned nuclear research has therefore motivated efforts to improve the experimental resolution in particle energy, mass, and charge currently obtained with existing 4π detector systems [4-7].

Improvements in the resolution of the above physical properties with large detector arrays depend crucially on the technology employed for the front-end electronics of these arrays. Crucial components are, in particular, large-bandwidth preamplifiers, as well as fast-timing and efficient (fast) pulse shape analysis methods. The present work discusses new developments of high-quality current-sensitive preamplifiers with large bandwidths that allow one to study the time dependence of intrinsic detector currents [8-9]. In addition, results are presented of studies of particle discrimination with large-area silicon elements of the 4π detector CHIMERA [10-11] based on simple pulse shape analysis.

It is well known that the timing characteristics of the current pulse produced by electron and hole collection in silicon detectors do not only depend on the intensity of the electric field along the particle track. In fact the detailed shape of a current pulse results from the interplay of rather complex physical phenomena arising along in the path of the ionizing radiation [12, 13]. Ionization density, electron/hole recombination, and effective charge separation vary along the particle
track and are influenced by the magnitude of the intrinsic electric field. Of most practical consequence is the realization that the shape of the current signal generated in the active region of a silicon detector depends strongly on which side the ionizing particle enters the detector. In front-side injection into a totally depleted n-type silicon detector of low or medium resistivity (~5000 Ωcm), a particle experiences a relatively high electric field only during the initial portion of its track, where the ionization density is small, while much of the ionization processes occur at a relatively low field strength. In contrast, in rear-side injection, most of the ionization induced at the later parts of the trajectory occurs at high field strength. The higher electric field strengths in the p-type region reduce recombination and produce high drift velocities of the holes, which are mainly responsible for the signal formation. This is why rear (n-side) particle injection into such an n-type silicon detector results in a greater variation of the pulse shape with particle species and better particle ID than front (p-side) injection. However, configurations with rear-side particle injection are not recommended for fast-timing applications. For the latter, front side injection leading to an early encounter of the high field is preferable, since it provides faster initial pulse rise.

For a given solid stopping material, here silicon, the profile of the ionization track (effective length and charge density) depends on basic properties of the ionizing particle, mainly its instantaneous effective charge and velocity. Thus the information regarding mass and charge of the particle of a given energy can be derived by studying the complete shape of the current pulse. While such a complete pulse shape analysis is possible with modern digital circuitry, practical tests have shown that already an analysis of the initial pulse rise time provides for adequate particle identification [14]. In such applications detector readout is performed with fast charge-sensitive, high-resolution preamplifiers [8].

Rise time measurements for PSD applications have recently been performed by Mutterer et al. [15]. The relatively small (~5 cm²) silicon detectors used in these studies were manufactured with a neutron transmutation technology (n-TD), had low resistivity and good homogeneity. Employing a configuration with rear-side particle injection, Mutterer et al. [15] achieved remarkably low energy thresholds (2.5 MeV/nucleon) for particle ID and charge identification up to Z ~ 10. However, these small, low-resistivity detectors are significantly different from the CHIMERA array elements, such that the results of the above study [15] can not be applied immediately to CHIMERA detectors.

Our present work is therefore aimed at extending a PSD method [4] based on a simple measurement of the charge signal rise time to the CHIMERA silicon detectors. These latter detectors have been manufactured (by Eurisys Mesures, France or by Micron, England) in float zone technique from n-type silicon. The elements have large (~25 cm²) sensitive areas and high resistivity (~8000 Ωcm). Since good time resolution with constant-fraction discrimination (CFD) is prerequisite for this time-of-flight (TOF) application, the CHIMERA Si detectors were configured for front-side injection [16]. As discussed above, such front-side injection of the particles is not ideal for optimum particle ID. Nevertheless, because of the potentially significant gains in utility of the CHIMERA silicon detectors for heavy-ion induced reaction studies, the present work was undertaken to study feasibility and optimum performance of simultaneous applications of PSD and TOF techniques.

II. EXPERIMENTAL METHOD

A. Off-line PSD simulation

Off-line PSD simulation and rise time calibration have been carried out in the Detector Test laboratory of INFN in Catania using commercially available NIM electronics, including a precision pulser generator (BNC model PB-4). A block diagram of the electronics is shown in Fig.1.

![Fig.1- Electronic setup used for both, off-line pulse rise time calibration and in-beam pulse shape discrimination (see text).](image)

Using a passive splitter, the negative input signal from the pulser is divided into two identical pulses. One of them is shaped and amplified by a spectroscopy amplifier (ORTEC 572) and serves as energy signal. The other pulse is fed into a timing filter amplifier TFA (ORTEC 474). The TFA output pulse is split again with a passive splitter. One of these signals is fed into a constant-fraction discriminator CFD (ORTEC 934) set for 20% of the rise time. This CFD is used to generate the start signal of a time-to-amplitude converter TAC (ORTEC 567). Therefore, the internal delay time for this CFD was fixed at 20 ns, as optimized in CHIMERA TOF measurements. The other CFD output pulse is split again into two pulses, which are further transformed, added, and fed into a trigger, essentially simulating a CFD with a 90% threshold. Specifically, one of the pulses is delayed by a variable amount, ranging between 20 ns and 140 ns, depending upon the pulse generator setting. The other pulse is inverted and attenuated by 10% (CAEN mod. N109). The resulting pulses are then added to-
gether, generating a crossover signal which is amplified using a fast timing amplifier (EG&G-ESN FTA410). The negative leading edge (LE) of the output signal triggers a discriminator (LeCroy model 620CL) providing the stop pulse for the TAC. This latter logic signal simulates an effective 90% CFD output signal. According to the scheme illustrated in Fig. 1, energy and time signals from the outputs of the spectroscopy amplifier and the TAC, respectively, are converted by two analogue-to-digital converters ADC (SILENA model 7423 UHS) read out by a PC based data acquisition system.

The response of the PSD setup (Fig. 1) to negative input pulses of 40-mV and 400-mV amplitude and the effect of changes in various parameters of the setup have been studied, and a calibration was obtained for the TAC in terms of the 20%-90% rise time of the primary input pulses. Pulses from the precision pulse generator had rise times between 50 ns and 500 ns, but a fixed decay time of 200 μs. With the TFA parameters set to 20 ns integration time (INT) and 20 ns differentiation time (DIFF), the TAC output showed a remarkably linear response to the input pulse rise times (50 ns - 500 ns). The TAC output was also carefully measured for the same range of primary input pulse rise times and TFA differentiation times varied from 50 ns - 500 ns, while the TFA integration time was held constant at 20 ns.

These simulation experiments demonstrate that the setup shown in Fig. 1 permits one to measure the rise time of primary input pulses in a wide dynamic range, where the TAC output pulse amplitude is a calibrated linear function of primary input rise time. For example, for the settings INT=20 ns, DIFF=50 ns, and “internal delay” of the “90% CFD” fixed at 20 ns, one obtains the relation
\[
Time(\tau) \approx a \times \tau + b
\]
between TAC output amplitude Time and primary rise time \(\tau\) of a pulse produced by the FTA module. Here, the calibration parameters turned out to be \(a = 1.2\) and \(b = 35.0\) ns. Plausibly, changing the internal delay of the “90% CFD” affects the calibration parameters \(a\) and \(b\). However, for purposes of the present analysis, knowledge about absolute rise times are not needed. The parameter Time is only used as a useful scale parameter for particle identification.

**B. In-beam PSD measurements**

The set up illustrated in Fig. 1 was also used to study PSD in in-beam experiments. These measurements were carried out with \(^{19}\text{F}\) beams of 85.75 and 95 MeV from the Tandem Accelerator of the LNS Catania and a \(^{12}\text{C}\) target. Two large area (~20 cm²) “two-Pad” silicon detectors of the CHIMERA array [16] were tested, coupled to low-noise, charge-sensitive preamplifiers especially developed for this purpose [8]. The detectors were placed inside the LNS 2000-mm diameter scattering chamber aligned at angles of 10° and 8° with respect to the beam direction. Detector configurations with front-side and rear-side injection were explored. The experimental set up was similar of the one described elsewhere [4].

The measurements included a study of the influence of the detector bias on PSD performance. In a typical run, one of the employed detectors (D1) at room temperature was biased to the full depletion value of ~38 V (nominal) resulting in a leakage current of about 0.6 μA. PSD spectra were then taken for different bias voltages. Within a range of ±15% of the full depletion voltage, no appreciable change resulted in the particle-ID energy threshold demarking the domain of satisfactory Z-resolution. Therefore, all other studies of PSD with this detector (D1) were carried out with the bias set at the nominal voltage of ~38 V.

The set up of the timing circuitry, including timing amplifiers and constant fraction discriminators, were kept within the experimental target area, at a distance of about 2 m from the detector. The split preamplifier and CFD digital signals were transmitted via 30-m long 50-Ω cables to the data acquisition site, where they were used for energy and time measurements, respectively.

In-beam studies performed at 85.75 MeV detected particles produced in \(^{19}\text{F} + ^{12}\text{C}\) reactions. Detector D1 was placed at an angle of 10° with respect to the beam direction fully exposed to the scattered beam from the target. The stability of the beam current around 500 pA was monitored by a Faraday cup placed at about 2 m from the target. Typical signals generated from elastically scattered \(^{19}\text{F}\) beam particles had rise times of about 40 ns, as observed with a 400-MHz oscilloscope (TEKTRONIX-2467B). In these measurements, the TFA integration time was kept constant at 20 ns, while other parameters were varied. For example, the TFA differentiation time was changed to 50 ns, and the effective internal delay of the “90% CFD” was varied by 20 ns. The TAC full range was kept at 200 ns in all measurements illustrated in the figures shown below.

A PSD spectrum (energy vs. time scatter plot) obtained in front-side injection mode is shown in Fig. 2. Placed at a dis-
tance of 40 cm from the target, the detector covers an angular range of ±3.5°, which corresponds to a wide acceptance for this inverse-kinematics scattering. The main feature of Fig. 2 is an intense ridge of yield associated with elastically and inelastically scattered 19F projectiles. In addition, ridges due to reaction products (O, N, C, B, Li, and α) are clearly discernible in this plot. At low energies, events distorted by edge effects and background are visible in this figure as well.

Energy calibrations for this and other plots (33 - 41 keV/ch) shown below were done using the maximum energy deposit in the detector by “punch-through” alpha particles and the energy of the elastic 19F peak at the mean detector angle, corrected for the pulse height defect. Time calibrations of the TAC (54 - 105 ps/ch) were carried out with cable delays.

To reduce changes in kinematics over the detector acceptance and variations in detector thickness, as well as to eliminate edge effects, a 1-cm diameter aperture was placed in front of the detector. Evidently, effects of the electric capacitance on spectral characteristics of noise and signal shape are not altered by an aperture.

Improved performance of the detector D1 with an acceptance limited by the above aperture is illustrated by the PSD plots of Figs. 3a and 3b. The data shown in these plots correspond to particles from the same reaction (19F + 12C), but at a slightly higher beam energy (95 MeV) and at an angle of 8° relative to the beam direction. As before, detector D1 was operated with front-side injection. PSD spectra were recorded with a TFA integration time of 20 ns and a differentiation time of 50 ns. The internal delay of the “90% CFD” was varied from 20 ns to 100 ns. Data of Fig. 3a and Fig. 3b were obtained with this internal delay set to 20 ns and 60 ns, respectively. The 60-ns internal delay corresponds to the best defined identification pattern. Figure 3a differs from Fig. 2 essentially only in the absence from the former of events due to rescattering or edge effects. The particle identification patterns obtained in both cases with similar electronics are practically unchanged. Therefore, on concludes that the size of the sensitive detector area does largely not influence the identification pattern. However, for consistency in the following only measurements are shown featuring apertures in front of the detectors.

Another CHIMERA detector (D2) of approximately the same size as D1 was tested for PSD performance. D2 was operated at room temperature with bias voltage of ~ 40V resulting in a leakage current of ~ 0.16 μA. The detector was placed at an angle of 8° with respect to the beam direction and with its rear side facing the target, i.e., in a geometry for rear-side injection. Detector acceptance was again defined by an aperture of 1-cm diameter. Particles from the 19F + 12C reaction at 95 MeV were measured again in this setup. PSD spectra were recorded with a TFA differentiation time of 100 ns and two settings (125 ns and 147 ns) of the internal delay of the “90% CFD”. The TAC full range was increased to 500 ns.

A PSD spectrum taken with the above (rear-side injection) configuration and a 147-ns internal delay is depicted in Fig. 4. Comparison of the patterns of yield ridges corresponding to different particles injected in the front (Figs. 3) with that of rear-side injection (Fig. 4) suggests slightly better resolution and more linear particle-ID response for the latter. Such behavior is expected from the different balance between ionization density and recombination discussed previously. However, the quality of particle identification achieved with these detectors is surprisingly similar in both cases.
III. RESULTS AND DISCUSSIONS

In spite of the high background contribution in the matrix of energy vs. time shown in Fig. 2, the different particles produced in the $^{19}$F + $^{12}$C reaction are well identified, even when no apertures are used and the detector is fully exposed to the scattered beam. Energy thresholds for particle-ID for the well identified particle species, such as nitrogen and carbon, were determined from the intersection of different ridges in the 2-D spectra (Fig. 2). The determination of the particle-ID energy threshold for oxygen is complicated because the corresponding yield is heavily contamination by tails of the intense ridge of elastically scattered fluorine ions. Contributions from background and edge events were reduced considerably with the use of apertures in front of the detector. Overall quality and separation of the identification patterns are enhanced by such a measure, as demonstrated by Figs. 3a and 3b relative to Fig.2.

Earlier, Mutterer et al. [15] reported on the particular efficacy of a PSD technique using rear-side injection of particles into n-TD and other silicon detectors. These measurements used particles from the $^{14}$N + $^{12}$C reaction at 150 MeV, which had somewhat higher energies and detectors of smaller dimensions than those of the CHIMERA array considered in the present work. It is therefore difficult to compare the performance of the present PSD method directly with that employed by Mutterer et al. [15].

Notice that, in the present study of the $^{19}$F + $^{12}$C reaction at 95 MeV, the energies of oxygen, nitrogen and carbon ions determined from different sets of data agree with each other to within ± 3 MeV. Average energies of the oxygen, nitrogen and carbon ions determined from the various sets of data are 71, 65, and 59 MeV respectively. There are some differences in the PSD response between rear-side and front-side injection. For example, the two injection methods lead to differences in the full range of pulse rise times, and relative rise times for detected particles of about a factor three were measured in the two configurations. However, no significant difference in the quality of the PSD identification was observed, as measurements yielded comparable particle-ID energy thresholds (cf. Table I and Table II). For front-side particle injection into the present large-area detectors, one observes an average particle-ID energy threshold of ~3.44 ± 0.05 MeV/nucleon. Best results were obtained with an internal delay of 60 ns for the “90% CFD.” This optimum internal delay coincides with that determined for rear-side particle injection.

Average particle-ID energy thresholds of the order of ~3.44 MeV/nucleon determined in this work for both injection types are not unusual for low-energy reactions. Mutterer et al. [15] observed a somewhat lower particle-ID threshold of 2.5 MeV/nucleon with a smaller area (5 cm$^2$) n-TD silicon detector. It is noteworthy however, that in the present work the above figure of merit has been achieved for 5-times larger, CHIMERA-type detectors manufactured from normal silicon, and without compromising good timing resolution (front-side entry).

Table I: Results for particle-ID energy thresholds: Front side injection
TFA settings: INT=20 ns, DIFF=50 ns (see text)

<table>
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<tr>
<th>Atomic Number</th>
<th>Threshold (MeV/nucleon)</th>
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<tbody>
<tr>
<td></td>
<td>90%-CFD delay =20ns</td>
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<tr>
<td>6</td>
<td>3.75</td>
</tr>
<tr>
<td>7</td>
<td>3.70</td>
</tr>
<tr>
<td>8</td>
<td>3.75</td>
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</tbody>
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Table II: Results for particle-ID energy thresholds: Rear side injection
TFA settings: INT=20 ns, DIFF=100 ns (see text)

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Threshold (MeV/nucleon)</th>
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<tbody>
<tr>
<td></td>
<td>90%-CFD delay=125ns</td>
</tr>
<tr>
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<td>3.44</td>
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<tr>
<td>7</td>
<td>3.49</td>
</tr>
<tr>
<td>8</td>
<td>3.51</td>
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Fortunately therefore a detector set up with front side injection is suggested that allows for an accurate measurement of the time of flight (TOF) with particle identification, based on simultaneous measurement of the pulse rise time. This finding opens up the possibility for an upgrade of just the CHIMERA electronics to achieve an efficient simultaneous charge and mass identification of low-energy particles with this 4π detector. Evidently, it is necessary to develop compact electronics circuitry incorporating the essential features of the set up used in the present measurements (cf. Fig.1) for the almost 1200 CHIMERA preamplifier output lines [11].

Fig. 4: Energy-Rise time correlation matrix obtained with detector D2 with aperture and rear-side injection.
The present work has studied application of a PSD particle-ID method for heavy-ion reactions at relatively low bombarding energy. In fact, the particle-ID energy threshold is the most crucial parameter to be taken into account in future applications. However, additional studies with this PSD set up are needed of reactions at higher bombarding energies, in order to determine to determine the performance of the method also for higher-energy particles in a broader range of atomic numbers. In particular, it will be very important to identify particle mass by a TOF method using pulsed beams with good timing properties. The aim of such experiments is to achieve low energy thresholds for both atomic and mass number identification, especially in the region of intermediate masses (10 < A < 50).

IV. CONCLUSION

In this work, an efficient PSD method has been developed for large-area, n-type (implanted) silicon detectors, which are especially configured for fast-timing applications. The method is based on the rise time measurement of charge signals obtained from fast preamplifiers with broad dynamic range. Rise time information was obtained from the difference in response times of two constant-fraction discriminators triggering at different pulse levels (fractions). Rear–side and front-side particle injection have produced particle ID of similar quality.

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VI. REFERENCES