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Charged particle identification using time of flight with FAZIA

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Summary. — This contribution reports on the time of flight implementation in the FAZIA Si-Si-CsI(Tl) telescopes, focusing on the basic ideas of the method and on some results from recent experiments at LNS.

1. – The FAZIA telescope array

FAZIA is a modern and innovative three-layer telescope (Si + Si + CsI(Tl)) array. The main characteristics of FAZIA are the modularity and the portability. In fact, FAZIA is expected to measure in various laboratories, in different geometrical setups and coupled to other detector arrays. Another important aspect is the capability to identify, with unitary mass accuracy, the highest possible number of ions produced in heavy-ion reactions around the Fermi energy. So far, we verified the identification in charge up to $Z \sim 55$ and in mass up to $Z \sim 25$. This goal was achieved using custom detectors produced following a well-studied recipe [1,2] and using original electronics with novel pulse-shape discrimination (PSD) techniques [3-5] based on high speed ADC with rates up to 250 MS/s and 14-bit resolution. The first experiments of FAZIA proved the capability to integrate inside the scattering chamber all the electronics required for silicon detectors and scintillators read-out by photodiodes. This very innovative and challenging electronics includes pre-amplifiers, analogue chains, high speed converters, read-out logic, high voltage devices and pulse generator for analogue chains. More details on the FAZIA apparatus can be found in [6, 7].

To implement the ToF technique, clock synchronization among all the digitizers is needed. In fact, if different ADCs had independent clocks, the accuracy of the time measurement could not be better than one clock cycle (4 ns for our fastest digitizer), unless a synchronization procedure is implemented (*e.g.*, [8]). Indeed, the simplest solution to synchronize the sampling ADCs is to provide exactly the same clock signal to all of them. FAZIA was designed keeping in mind the possibility to measure time marks, thus a sophisticated clock distribution was implemented: the primary clock is generated outside the scattering chamber and distributed through optical fibers to the blocks (a block, composed of 16 telescopes and their acquisition chain, is the "atomic" unit of FAZIA). The link was optimized to provide a fixed latency and an extremely reduced clock skew [9]. Due to the physiological delays between clock edges and ADC sampling, practically the various sampled signals are not exactly synchronous, since the delays are not identical among the ADCs. A method to reduce the residual asynchronism, which can even exceed 1 ns, is investigated in sect. **3**˙3.

2. – Time of flight implementation

Thanks to PSD, FAZIA has relatively low identification thresholds (down to ∼5 MeV/u for light fragments). The Time of Flight (ToF) information could be used to further reduce the mass identification thresholds, also in the perspective of using FAZIA at the new ISOL facilities (*e.g.*, SPES and Spiral2). Our Collaboration recently renewed important efforts in this direction [10, 11]. Once the ToF of a particle is measured, the mass discrimination is possible by correlating that quantity with the energy released in the first Si layer. Several detectors for heavy-ion studies already implemented E-ToF identification (*e.g.*, [12]), but a precise time mark extraction in FAZIA is more challenging than usual for many reasons:

- we use large area ($2 \times 2\,\mathrm{cm}^2$) and reverse-mounted Si detectors;
- we use a relatively short flight base (1 m);
- signals are slowed down by an anti-aliasing filter before sampling.

Time of flight implementation requires a start and a stop time mark. The ToF is the difference between the two time marks. Usually, the start time mark is given by a dedicated sensor (not feasible with high granularity detectors like FAZIA) or by the accelerator radio-frequency (available with pulsed beams only). We implemented a method to recover the start time mark from the measured energy E_{ref} of a fully identified particle (*i.e.*, a particle with known mass m_{ref}). The procedure was first described in [13], it is valid only for at least two-fold coincidence events and it is sketched in fig. 1.

To apply our procedure to an unknown particle we need, within the same event, at least a reference ion. Knowing the flight base d_{ref}, the kinetic energy E_{ref} and the mass m_{ref}, we calculate the ToF for the reference fragment. The time of the reference ion production can be obtained from the ToF and the hit time in the detector and it is the same (within reaction times, which are negligible) also for the unknown particle because they are produced in the same collision. Thus we obtain the ToF of the unknown particle by the difference between its hit time and the previously calculated reaction time mark.

Hit time marks are obtained via a digital Amplitude and Rise-time Compensated Constant Fraction Discriminator (ARC-CFD). The time mark t_x corresponds to the zero crossing of the bipolar signal built as the difference between the charge signal reduced by a factor f and the same signal, not reduced, delayed by a time t_D. After many tests we found that the best setting for our detectors is $f = 20\%$ and $t_D = 20\,\mathrm{ns}$. The error

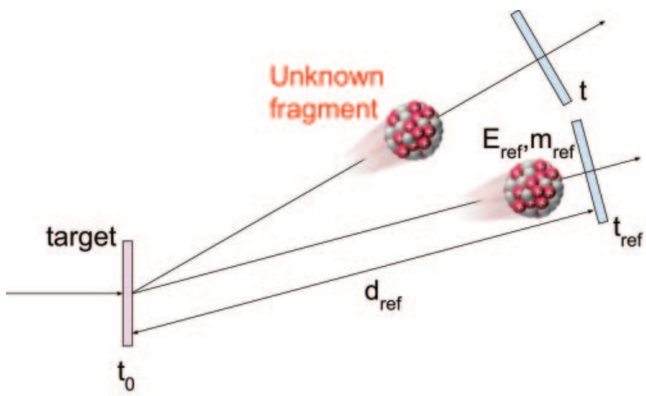

Fig. 1. – Our implementation of a ToF measurement not needing a start detector or accelerator RF (more details in the text).

on the time marks σ_t is mainly due to the jitter (eq. (1)), since the ARC-CFD procedure minimizes the amplitude and rise-time walk,

$$\sigma_t = \frac{\sigma_s}{\dot{s}\,(t_x)} \frac{\sqrt{1+f^2}}{1-f}. \tag{1}$$

In eq. (1), which is exact for a linear ramp signal, σ_s is the error on a signal sample (due to electronic noise) and $\dot{s}(t_x)$ is the signal derivative calculated at the zero crossing time. If we calculate the error on ToF obtained with our implementation for two isotopes of carbon at 25 MeV, we can conclude that the E-ToF method can discriminate the isotopes. The energy of 25 MeV was chosen because it is the charge identification threshold for carbon with PSD, while, with the same technique, the mass separation is reached at 60 MeV. So, in principle, our method can considerably improve isotopic discrimination and we expect to extend mass identification to hydrogen isotopes (not resolved at all with PSD in FAZIA) and charged particles up to $Z \sim 10$ with an energy threshold of around 1 MeV/u for lighter ions.

3. – Results

3˙1. *First application to experimental data.* – Our implementation of ToF measurement needs at least a fully identified particle, thus we performed the first tests of the method using the data from the first FAZIA experiment. The results (showed in fig. 2) were partly unexpected. On one hand we recovered the isotopic discrimination of hydrogen isotopes, on the other we were not able to clearly resolve any other ion.

While studying this behaviour, we found that the actual sampling times are not the same for the various ADCs, as was anticipated in sect. **1**. Different relative delays

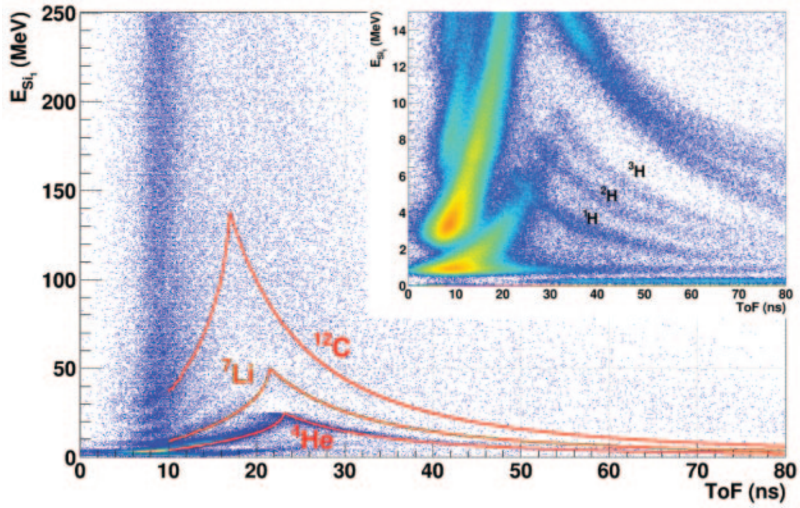

Fig. 2. – E-ToF correlation for a typical first layer silicon detector during the first FAZIA experiment. The start time mark is obtained from reference particles detected in any FAZIA telescope (see text).

introduce systematic errors in the ToF calculation for the reference fragments, depending on the front-end electronic channel involved, thus spoiling the final ToF resolution. So, even if a refined clock distribution is applied in FAZIA, it is necessary to correct the different delays introduced by each ADC sampling.

3˙2. *Channel synchronization with LED.* – To estimate and correct the systematic effect described above, a fast infrared pulsed LED is used to illuminate the first Si layer (*i.e.*, the one used for timing) of every FAZIA telescope. The pulse width and amplitude are chosen in order to produce reasonable signals inside the first silicon layer (not saturating but still using a large fraction of the ADC range). The infrared frequency was adopted to be sure to punch through the thin aluminium layer in front of our sensors. The time of flight of the LED pulse is exactly proportional to the distance between the LED and the sensor, thus we can easily build a delay map of FAZIA detectors. In particular, we choose a reference silicon and we make a map of the differences between ARC-CFD time marks of every detector and the reference time mark. Then, the delay map can be used to correct the time marks obtained in physics events.

We tested our channel synchronisation method with two sensors on a test bench by adding at a certain phase of the test a plexiglas block on the light path between the LED and one sensor. Considering the diffraction index and its length, the plexiglas block nominally added 207 ps to ToF. Before adding the block, we observed a sizeable time mark difference between the signals from the two sensors. The difference should have been close to zero, since the distance between the LED and both detectors was almost the same. However, adding the plexiglas, the difference shifted by $\{198 \pm 8\}$ ps, a value which is compatible with the nominal delay added by the block.

During one of the latest experiments we repeated the plexiglas test, by illuminating all the FAZIA detectors and putting the plexiglas delay in front of some random telescopes. We always obtained a measured delay compatible with 207 ps, thus we concluded that the LED synchronisation procedure permits to correct ADC delays with an accuracy down to $\sim$10 ps. During the last FAZIA experiments LED pulses were acquired (they were always on with a 0.1 Hz rate) and used to correct the ADC delays. Thanks to LED events we observed that the sampling delays remained stable during all the experimental run, while they varied only when the electronics was rebooted.

3˙3. *Channel synchronization with correlated particles.* – Recently, an alternative method which does not need a pulsed LED was also developed. Since a dedicated hardware (LED and pulse generator) is not needed, we can apply the delay correction also to old experiments. This new method, which proved to be as precise as the LED correction when enough statistics is collected, uses a subset of the experimental data. In particular we take into account all the events where at least two particles are fully identified in energy and mass. Since the two particles come from the same event, they share the reaction time mark. From energy, mass and detection time mark we can recover the "raw" reaction time marks, which do not have the same value. Their difference represents the difference between the channel delays. As described before for the LED synchronization, with these obtained differences we are able to fill a delay map that can be used to correct the hit time marks in the physics events.

The final improvement on the isotopic discrimination can be easily noticed in fig. 3. As expected from jitter estimations, we are able to discriminate isotopes with energy thresholds going from 0.5 MeV/u for $Z = 1$ to 10 MeV/u for $Z = 10$.

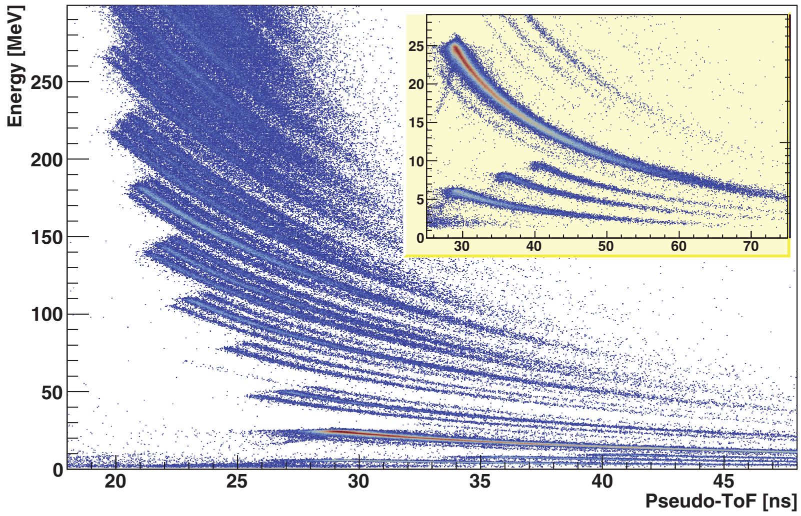

Fig. 3. – E-ToF correlation obtained from one of the last FAZIA experiments. The light charged particles region is plotted in the inset. Time marks were corrected with a delay map obtained from correlated particles (see text).

4. – Conclusions

In this contribution we propose a method to extract the start time mark for the ToF measurement which does not need a dedicated sensor or the acquisition of the RF signal from the accelerator. We tested the method on the first fully calibrated FAZIA experiment, but unfortunately the obtained ToF resolution was poor due to the residual relative delays between the sampling times of the different ADCs. To correct for this systematic effect, we implemented two independent procedures. One uses fast infrared LED pulses to synchronize the channels, the other uses measured particles instead: in these ways we correct the time marks obtained in our experiments. The time correction maps for the various detectors were obtained during the last FAZIA experiments and they were used to produce E-ToF correlations. Overall, the ToF identification permits to improve mass discrimination with respect to PSD for particles with $1 \leq Z \leq 5$, opening the door to the study of light particles emitted by quasi-target fragments in deep inelastic collisions.

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