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Time of flight identification with FAZIA

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Summary. — FAZIA (*Forward A and Z identification Array*) is an array of three-stage Si-Si-CsI(Tl) telescopes. It was designed to operate with beams in the 20–100 MeV/u energy range and it provides charge and mass discrimination over a wide range of nuclei and energies. In the perspective of FAZIA experiments at lower energies (*e.g.* to be realized at the new ISOL facilities SPES and/or Spiral2), and in general to lower the identification thresholds, the time of flight (ToF) information could be used. Usually, the time of flight can be obtained in two ways: either two detectors (start and stop) are used at a certain well-measured distance, or the start time mark is given by the accelerator RF signal. In order to work also in the absence of pulsed beam, we are studying and implementing a new approach that works for those events where at least one ejectile is properly discriminated in mass. The identified fragments can be used to extract the event start time mark from their energy and mass. This algorithm needs a perfect synchronisation among all the ADC clock signals and a precise tuning of all the possible clock skews. This contribution reports on such recent FAZIA activity, focusing on the basic ideas of the method and on some first 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 setups and coupled to several detectors. Another important aspect is the capability to identify with unitary mass accuracy the highest possible number of ions produced in heavy-ion reactions around Fermi energy. In the present situation, we clearly discriminate charges up to $Z \sim 55$ and masses 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 analog-to-digital converters with rates up to 250 MS/s and 14-bit resolution. The commissioning runs 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.

1˙1. *FAZIA electronics.* – The first feature which could be noticed when looking at the FAZIA apparatus is the absolute scarcity of electronic racks outside the scattering chamber. In fact, the so-called regional board (RB) is the only electronic card placed outside and it performs the functions of a standard "event building" card. Only two connections per block are necessary: a 48 V power supply line and a 3 Gbit/s full-duplex optical link used to transfer data, to synchronise the clocks, to send triggers, and to manage any block parameter via slow control.

Inside the vacuum chamber, the basic element of the FAZIA array is the block (see fig. 1), which consists of 16 detector telescopes. The telescopes are connected to 8 front-end electronic (FEE) cards, which feature, among other components, charge sensitive pre-amplifiers, ADCs, Si bias voltage regulators, and FPGAs for data handling. Up to two

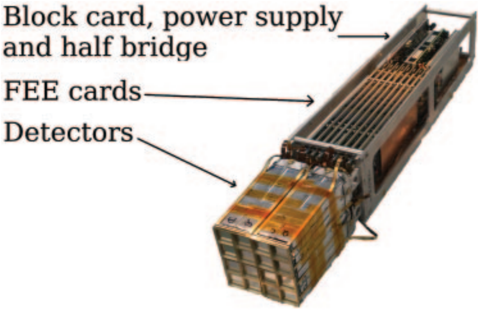

Fig. 1. – Picture of a FAZIA block. The detectors and the front-end electronics are highlighted.

telescopes can be connected to each front-end card. All the FEE cards are connected to a "Block Card" via a common backplane, which hosts also two power supply boards. The Block Card (BC) is mainly devoted to handle I/O operations and to merge data coming from the FEE cards. Power Supply (PS) and Half Bridge (HB) cards produce and monitor the voltages needed to the other boards on the block. The FAZIA blocks communicate with the event building electronics via the Block Card through the 3 Gbit/s optical link. A metallic housing covers all the block; there is also a metal screen around the BC, PS and HB cards to avoid that electromagnetic emissions from DC/DC converters reach the FEE cards. All the electronic cards of the block are supported by (and firmly screwed to) a copper plate in which water can flow for cooling. More details on the FAZIA electronics can be found on [6].

1·2. *Clock distribution.* – To implement the ToF technique, clock synchronisation among all the ADCs is needed. In fact, if the ADCs in different blocks had independent clocks, the accuracy of the time measurement could not be better than one clock cycle (4 ns for our fastest ADCs). So, to synchronise all the sampling ADCs, they must be provided with exactly the same clock on all the cards. FAZIA design was performed keeping in mind the possibility to measure time marks, thus a sophisticated clock distribution was implemented.

The primary clock is generated on the regional board: there are two crystal oscillators set at 125 MHz and 150 MHz and both are connected to the FPGA chip. The former is used only for the Ethernet part. The latter is used to generate (inside the FPGA) a 25 MHz clock and to clock the built-in GTX transceivers, which are used to send and receive data from the blocks through the optical link. The transceivers are devices embedded inside the FPGA. In our case they convert 16-bit data at 150 MHz (2.4 Gbit/s) to a serial line at 3 Gbit/s and vice versa. The missing 1.25 factor in the data rate comes from the 8b/10b coding of the serial line. Xilinx GTP and GTX transceivers are very suitable to implement a connection with fixed latency, as they can provide an extremely reduced clock skew [7].

The optical fibres leaving the regional board enter the scattering chamber and reach the various blocks. They are connected to the SFP optical translators on the block cards. The signals eventually arrive inside the block card FPGAs, where they are de-serialised by GTX transceivers. The BC has a peculiar system to recover the 25 MHz clock from the optical link: on the card there is a voltage controlled crystal oscillator (VCXO), connected to a phase-locked loop (PLL) device, which is used to clock the FPGA. The

PLL reference is the signal recovered from the fibre by the FPGA itself. When the BC is switched on, the PLL is not locked and the FPGA is clocked by a 25 MHz signal that is uncorrelated with the 25 MHz signal generated on the regional board. Then the block card starts to catch a special sequence (sent by RB every 40 ns) from the optical link and generates the synchronised 25 MHz signal that enters into the PLL device. At this point the PLL is locked and so is the FPGA clock. The PLL output is also split into eight outputs that reach the FEE cards through the backplane. The front-end cards use the phase-locked 25 MHz signal to produce (using VCXO and PLL devices) 100 MHz and 250 MHz frequencies. Finally, these signals are used to clock the the FPGAs and the ADCs. 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, of the order of 100 ps, is investigated in sect. 3.2.

2. – Time-of-flight implementation

2˙1. *Identification methods.* – The three layers of FAZIA telescopes allow the use of two different ΔE-E correlations [8] to identify ions: in particular, by correlating the energy released in the first Si layer *versus* the energy released in the second one, it is possible to discriminate charge and mass of ions stopped in the second silicon detector; instead, by correlating the total energy released in both Si sensors *versus* the light output detected in the CsI(Tl) scintillator, it is possible to fully identify the lightest and fastest fragments which punch through the second Si layer. Moreover, as already mentioned, FAZIA exploits pulse-shape discrimination to identify the slowest fragments, which stop inside the first layer. The overall identification capability of FAZIA, obtained by combining ΔE-E and PSD, is to discriminate ion charges up to $Z \sim 55$ and masses up to $Z \sim 25$, with an energy threshold of about 2 MeV/u (5 MeV/u for mass discrimination).

In the perspective of FAZIA experiments to be realised at the new ISOL facilities (*e.g.*, SPES and Spiral2), and in general to further lower the identification thresholds, the time-of-flight (ToF) information could be used. Our collaboration recently renewed important efforts in this direction [9, 10]. 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. We expect to recover mass identification for Hydrogen isotopes (not resolved at all with PSD) and charged particles up to $Z \sim 10$ with an energy threshold of around 1 MeV/u.

2˙2. *ToF measurements.* – In any kind of physics experiment, time of flight implementation needs a start and a stop time mark. The ToF is the difference between the two time marks. Usually, two techniques are adopted:

- The start and the stop time marks are given by two detectors. We cannot easily implement this solution, since FAZIA is composed of many detectors at 1 m distance from the target. It would be almost impossible to put, for each telescope, a corresponding very small detector near the target.

- The stop time mark is given by a detector, while the start one is recovered from accelerator radio-frequency (RF), which must be sampled with the same clock of the experimental apparatus. In fact, if we have a bunched beam, the difference between the RF time mark and the collision time is fixed (modulo the bunching period). Unfortunately, this method cannot be always applied, since not all the

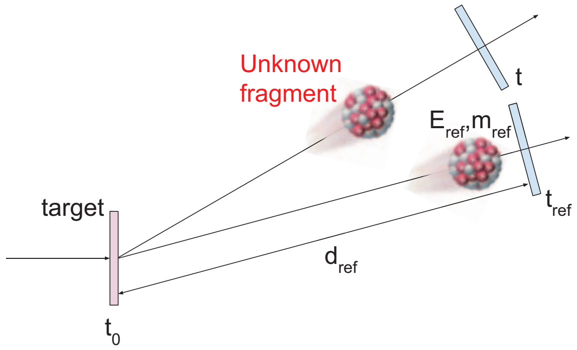

Fig. 2. – Our implementation of ToF measurement which does not need a start detector or accelerator RF. More details in the text.

accelerators can produce bunched beams. Moreover, asking for a precise RF timing usually implies a substantial lowering of the beam current.

2˙3. *Our implementation*. – We decided to implement a new method, which does not need a start detector: the start time mark is recovered from at least one detector that fully identified a particle. The procedure was first described in A. Buccola Master Thesis [11] and it is briefly illustrated in fig. 2.

To apply our procedure to an unknown particle we need, inside the same event, at least a reference ion (of which we know the mass $m_{\rm ref}$ and the kinetic energy $E_{\rm ref}$). By inverting the kinetic energy formula and knowing the flight base $d_{\rm ref}$, we can easily calculate the ToF (and thus the start time mark) for the reference fragment. The obtained start time mark is the same also for the unknown particle because the collision is the same. So, if we measure the stop time mark via a digital *amplitude and rise-time compensated constant fraction discriminator* (ARC-CFD), we have also the ToF.

The error on the time marks is mainly due to the jitter (eq. 1), since the ARC-CFD procedure should minimise amplitude and rise-time walk (which we consider negligible):

$$\sigma_t = \frac{t_{rise}}{\mathrm{SNR}} \frac{\sqrt{1+f^2}}{1-f}. \tag{1}$$

In the formula, which is exact for a linear ramp signal, t_{rise} is the full rise-time (from 0 % to 100 % of the maximum amplitude), SNR is the *signal-to-noise ratio* and f is the fraction of the maximum amplitude at which the ARC-CFD is calculated.

If we calculate the error on time of flight obtained with our implementation for two isotopes of carbon at 25 MeV (see fig. 3), we can easily conclude that this method can discriminate the isotopes. The energy of 25 MeV was chosen because it is the charge identification threshold for carbon with PSD. Indeed, to have mass discrimination with pulse-shape we need at least 60 MeV carbon ions. So, in principle, our method can considerably lower the energy thresholds for mass discrimination.

3. – First application to experimental data and channel synchronisation

3˙1. *ISOFAZIA experiment*. – Our implementation of ToF measurement (see sect. 2.3) needs at least a fully identified particle, so we tried to apply it to the ISOFAZIA

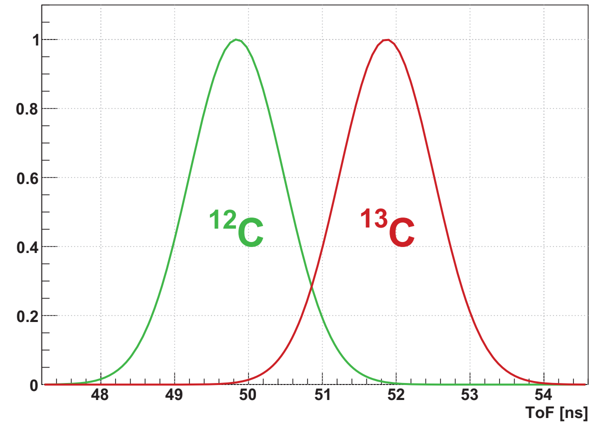

Fig. 3. – Expected ToF distribution (where the width is due to the jitter) for ^{12}C and ^{13}C ions at 25 MeV detected on a flight base of 1 m. The two isotopes are clearly discriminated.

experiment, because the calibration and particle identification phase was already concluded for this campaign. The results (showed in fig. 4) were partly unexpected. On the one hand, we obtained the isotopic discrimination of hydrogen isotopes (impossible with PSD), on the other, we were not able to clearly resolve any other ion.

The explanation of what we observed can be found in sect. 1.2. In fact, as previously stated, the various sampled signals in FAZIA are not exactly synchronous, even with a refined clock distribution.

3·2. *Channel synchronisation with LED.* – To correct the different delays of each ADC, we decided to illuminate all FAZIA detectors with a fast infrared pulsed LED. The pulse width and amplitude were chosen in order to have reasonable signals inside the first silicon layer (not saturating but still using a large fraction of the ADC range).

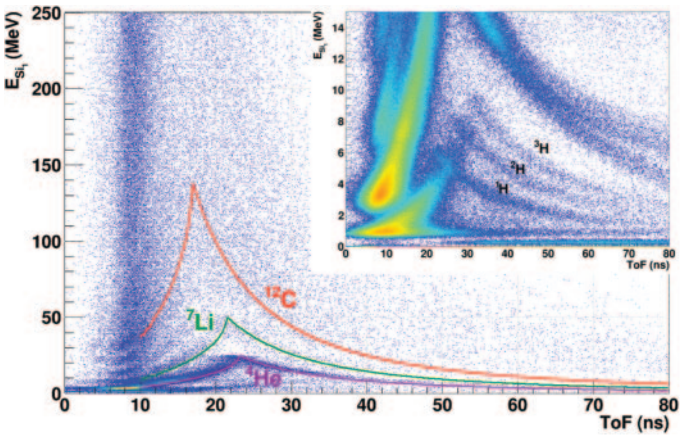

Fig. 4. – E-ToF correlation for a typical first layer silicon detector during ISOFAZIA experiment. Only Hydrogen isotopes are resolved.

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 point 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, shifted the difference by 198+-8 ps, a value which is compatible with the nominal delay added by the block.

During the latest experiment (FAZIAPRE) 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 may permit to correct ADC delays with a precision down to 10 ps. During FAZIAPRE the LED pulses were kept always on with a rate of 0.1 Hz. In this way we also checked the stability of the ADC delays.

4. – Conclusions

In this contribution we proposed an innovative method to extract the start time mark for the ToF measurement. We tested the method on a fully calibrated experiment, but unfortunately the physiological delays between clock edges and ADC sampling spoiled the results. To correct the delays we implemented a procedure which uses fast infrared LED pulses to synchronise the channels. In this way we corrected the time marks obtained in our latest experiment. However, since we need a full identification of reference particles, it was not possible to plot a E-ToF correlation for FAZIAPRE. In fact, for this experiment, the calibration and identification process is still in a early phase.

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